

# UNCLASSIFIED

<b>AD NUMBER</b>
ADB196664
<b>NEW LIMITATION CHANGE</b>
<b>TO</b> Approved for public release, distribution unlimited
<b>FROM</b> Distribution: DTIC users only.
<b>AUTHORITY</b>
NRL notice, 30 Sep 98

THIS PAGE IS UNCLASSIFIED

File

ATTI No. 175716  
ASTIA FILE COPY  
S T I

GEIGER COUNTER TUBES

H. FRIEDMAN

25 MAY 1949

DTIC  
ELECTE  
MAR 08 1995  
S G D

NAVAL RESEARCH LABORATORY

DTIC QUALITY INSPECTED 8

19950125127

50 Available For	
NTIS CRA&I DTIC TAB Unannounced Justification	<input type="checkbox"/> <input checked="" type="checkbox"/> <input type="checkbox"/>
By _____ Distribution /	
Availability Codes	
Dist	Avail and/or Special  12

## Geiger Counter Tubes

Since the first demonstration of the tube counter by  
(1)  
Geiger and Muller in July 1928, the unusual sensitivity of  
such counters has found widespread applications in the de-  
tection of high speed particles and energetic photons.  
The extensive literature on Geiger counters is not only  
indicative of their manifold uses, but is also a measure  
of the divergence of theories devised to explain their  
mechanism and the numerous recipes prescribed for the pre-  
paration of good counters. In the last ten years, however,  
a consistent and relatively complete theory of counter tube  
(2 - 8)  
operation has been developing together with a know-how for  
their construction which now permits production of large

1. H. Geiger and W. Muller, Physik. Zeits. 29, 839(1928);  
30, 489(1929)
2. A. Trost, Zeits. f. Physik 105, 399(1937)
3. C. G. Montgomery and D. D. Montgomery, Phys. Rev. 57,  
1030(1940)
4. W. E. Ramsey, Phys. Rev. 57, 1022(1940)
5. H. G. Stever, Phys. Rev. 61, 38(1942)
6. S. A. Korff and R. D. Present, Phys. Rev. 65, 274(1944)
7. A. Nawijn, Physica 9, 556(1946)
8. A. G. M. Van Gemert, H. Den Hartog, F. A. Muller, Physica  
9, 556(1946)

19950125 127

numbers of reliable tubes with identical characteristics. This paper is a review of current theories of the mechanism of the Geiger counter discharge and a survey of the many different types of counters designed for specialized applications.

A Geiger counter is a gas filled diode operated in the region of the unstable corona discharge. There are two types of counters characterized by their filling gases. One uses simple monatomic or diatomic gases such as hydrogen, air, the rare gases, or mixtures of these and is known as the non-self-quenching type. The second category includes mixtures of simple gases and small percentages of "quenching" admixtures, which are usually polyatomic organic molecules. In general, the firing characteristics of both types of fillings are very much alike, but the subsequent stages of the discharge and the deionization processes are distinctly different. The emphasis in this paper will be devoted almost entirely to a description of the self quenching type of tube which is now used almost universally in preference to the simple gas type. The condition for starting a discharge is that at least one low energy electron be produced within the counter gas. This electron kindles an avalanche discharge which spreads rapidly throughout the length of the tube and lasts for a few microseconds. Within a fraction of a milli-

second after the triggering event, all ions and electrons are cleared out of the inter-electrode space and the tube is ready to respond again to the passage of another ionizing particle. A single electron is capable of triggering a discharge which can be easily detected with little or no amplification. In this respect, the Geiger counter comes close to fulfilling the requirements of a perfect detector.

The electrode system of a Geiger counter usually consists of a fine wire and coaxial cylinder. Most tubes are filled with a rare gas combined with a trace of a polyatomic vapor such as alcohol, ether, amyl acetate, and many others. At low voltages, the tube behaves as an ionization chamber with an internal amplification factor of unity. A relatively small potential difference prevents recombination losses and is sufficient to draw a saturation current from the tube, supplied entirely by the primary ionization. Raising the voltage brings on gas multiplication by impact ionization of the gas molecules in the manner of the familiar Townsend avalanche. The multiplication factor increases with increase in voltage and the current delivered by the tube is proportional to the primary ionization up to multiplications of  $10^5$  or  $10^6$ . Throughout this range, the discharges are single Townsend

avalanches, each avalanche originating from a primary ion pair and localized within a fraction of a millimeter along the length of the wire. At still higher voltages every avalanche breeds new avalanches, spreading the discharge along the full length of the tube, through the medium of the very short wavelength ultraviolet rays generated in each Townsend avalanche. The discharge continues to burn until a critical space charge density of positive ions is reached. The amplification factor then becomes independent of the amount of primary ionization and all discharge pulses attain equal amplitudes. This condition characterizes the operation of the Geiger counter. Geiger counting threshold is usually determined experimentally by observing with an oscilloscope coupled to the simple circuit of fig. (1), the lowest voltage at which all pulses become equal in size. As threshold is approached, statistical fluctuations in the breeding of new avalanches from preceding avalanches may interrupt the chain before the discharge has filled the entire length of the tube. The transition to Geiger counting is ordinarily very sharply defined, as is illustrated in Fig. (2) which shows the rapid transition from incomplete growth of the discharge characterized by non-uniform pulse heights, to the threshold where each discharge has spread throughout the tube. The number of discharges is directly related to the number of primary particles striking the tube

and does not depend appreciably on the applied potential over a range of a few hundred volts known as the "plateau". At higher voltages, the condition of a self-sustained corona is reached and the discharge maintains itself until the potential is removed. Sufficiently high potentials bring on the transition to a glow discharge in which the current rises very rapidly and the voltage across the electrodes falls to a low stable value. The complete voltage characteristic of the cylindrical ionization tube is illustrated in Fig. (3).

Since the gradient of the electric field between a fine wire and a cylinder is very high in the immediate neighborhood of the wire, electron multiplication in the Geiger counter plateau range is confined to a narrow zone only a few wire diameters in width. Electron collection is accomplished in a fraction of a microsecond, during which the positive ions form a virtually stationary sheath about the wire. The eventual severing of the chain of electron avalanches is attributable to the electrostatic shielding effect of this positive ion sheath. Subsequently the ion sheath must be neutralized without reigniting the discharge. This constitutes the major problem in obtaining successful counter tube performance.

At first glance, the structure and mechanism of the Geiger counter appear to be deceptively simple. The complete Geiger counter mechanism is rather complex and involves: (1) the Townsend avalanche, (2) the spreading of the discharge, (3) the motion of the ion sheath and growth of the pulse, (4) the deionization process, (5) all the effects involved in suppression of spurious pulses. This last category includes: ionization transfer from positive ions of the rare gas to polyatomic vapor molecules, suppression of secondary emission at the cathode, quenching of metastable states, and photo-decomposition of the polyatomic gas.

The performance of any particular Geiger counter is described by its threshold voltage, the length and slope of its plateau, its efficiency, pulse characteristics, maximum counting rate, temperature dependence, and useful life. No single type of counter exhibits all the ideal characteristics, but some tubes meet the requirements of specialized applications almost to perfection.



### The Townsend Avalanche

The electric field strength between coaxial cylinders is given by

$$E(r) = \frac{V}{r \log \frac{b}{a}} \quad (1)$$

where  $E(r)$  is the field at distance  $r$  from the axis,  $V$  is the applied potential difference, and  $b$  and  $a$  are the cathode and anode radii respectively. Consider a typical counter, operating with an applied potential difference of 1000 volts. The field strength at the surface of the wire is about 40,000 volts per cm. It falls inversely as the distance from the wire and is less than a few hundred volts per centimeter at distances greater than  $b/2$  from the anode. Immediately after the passage of an ionizing particle the secondary electrons which it produced, are accelerated radially toward the wire. Each electron gains energy which it loses thru inelastic collisions leading to excitation or ionization of the gas. Every inelastic collision brings the electron to rest, after which it starts to travel its next free path in the direction of the field. The excited molecules may radiate their energy or be de-excited by subsequent collisions. If, for example, the counter is filled with hydrogen to a pressure of 100 mm Hg, the electron mean free path is about  $10^{-3}$  centimeter and sufficient energy for

impact ionization cannot be gained in one mean free path until the electron reaches the high field region very close to the wire. The potential fall per mean free path at the cathode is as little as 0.2 volts, but rises to about 20 volts at the surface of the wire. This energy gained per mean free path, first reaches the ionization potential of the hydrogen molecule, 16 ev, at a distance of four free paths, which is slightly less than one wire radius from the surface of the wire. Beyond the immediate neighborhood of the wire, the energy for ionization can be acquired only over several mean free paths.

Increasing the voltage across the counter toward the threshold for Geiger counting expands the multiplication zone in the gas over an increasing number of mean free paths. More and more electrons are added to the avalanche together with photons radiated from excited states of higher energy which are capable of photoionizing the gas or photoelectrically releasing electrons from the cathode. These photoelectrons are in turn accelerated toward the wire where they contribute new avalanches. Geiger counting threshold is marked by the release of a sufficient number of photons per avalanche to guarantee the generation of a succeeding avalanche by photoelectric effect in the gas or at the cathode.

The properties of the single Townsend avalanche can

generally be summarized as follows: at threshold the multiplication factor in the avalanche is about  $10^5$ ; each avalanche is quite discrete, and the lateral extension along the length of the wire arising from diffusion of the electrons in the avalanche is about 0.1 mm; the duration of the single avalanche is less than  $10^{-9}$  seconds measured from the beginning of the multiplication process.

The threshold voltage for the corona discharge depends for the most part on the nature of the gas as characterized by the first Townsend coefficient,  $\alpha$ , which is defined as the ionization produced by an electron per volt of potential difference. This coefficient,  $\alpha$ , depends on the energy gained by an electron per mean free path, which is a function of the ratio of field strength,  $E$ , to pressure,  $p$ . The threshold requirement that each avalanche release a sufficient number of quanta to photoelectrically trigger another avalanche is expressed in terms of a second coefficient,  $\gamma$ , as

$$n\gamma = 1 \quad (2)$$

where  $\gamma$  is the number of photoelectrons ejected per ion pair formed in the gas and  $n$  is the number of ion pairs per Townsend avalanche. Experimentally it is observed that  $\gamma$  for the simple gases does not vary markedly with different cathode materials, but that the nature of the gas, its

pressure, and the electrode geometry, as reflected in  $\alpha$ , are the quantities which are mainly responsible for establishing the threshold voltage.

Among the diatomic and inert gases, equal values of  $\alpha$  are achieved at widely different values of  $E/p$ . The rare gases, helium, neon, argon, krypton and xenon, produce higher threshold voltages in the order of increasing atomic number. Hydrogen requires a higher starting voltage than argon, and that of air or nitrogen is still higher. Traces of impurities have a pronounced effect on the starting voltage of the corona, as will be shown in a later section. Most present day counter tubes include a small percentage of a polyatomic "quenching" gas in addition to the rare gas which is usually the major constituent. Although the ionization potential of this polyatomic constituent is always lower than that of the rare gas, its presence almost invariably raises the threshold voltage. This is so, because a large portion of the electron energy is dissipated in exciting molecular vibrations at each impact, rather than ionizing. Polyatomic molecules with absorption bands in the near infrared portion of the spectrum can absorb energies amounting to a fraction of an electron volt, or less than the energy acquired by an electron per mean free path even in the neighborhood of the

cathode. Inelastic collisions can therefore bring the electron to rest every time it encounters a polyatomic molecule. In contrast to the simple gas fillings, an electron is much less likely then to acquire ionization energy over several free paths. As a result the zone of ionization contracts with addition of the polyatomic gas and the minimum field strength for a corona discharge increases. Argon with alcohol admixture is one of the most commonly used Geiger counter fillings. Fig. (4) illustrates the effect of argon pressure, percentage of alcohol admixture, and the size of the electrodes, on the threshold voltage.

#### Spread of the Discharge and Formation of the Ion Sheath

Above the threshold of Geiger counting, thousands of Townsend avalanches per centimeter of length of the tube are ignited through the emission and absorption of ultraviolet light. Neutral gas molecules are excited by electron impacts in the avalanche process and in returning to the ground state, emit ultraviolet quanta with energies below the ionization potential of the gas. If the counter tube is filled with simple gases, the ultraviolet photons generate new avalanches by releasing photoelectrons at the cathode. The rate of spread of the discharge is then dependent only on the lifetime of excited atoms or molecules and on the photon transit time.

If a polyatomic vapor admixture such as alcohol is included with the simple gas, the photon mechanism is very much altered. In a mixture of argon and alcohol the highest excited states of argon at about 11.6 ev exceed the energy required to ionize an alcohol molecule, 11.3 ev. Energetically, it is therefore possible for the ultraviolet photon radiated by an argon atom to ionize a molecule of alcohol, and thereby release an electron which may trigger a new avalanche. The efficiency of such absorption processes is so great that the number of quanta arriving at the cathode is insufficient to provide any significant number of photoelectrons. In addition to the absorption of ultraviolet quanta by the polyatomic gas, there is evidence for absorption processes in the rare gas itself, although their mechanism at present is not well understood.

Many investigations have been attempted with the object of identifying the nature of the ultraviolet radiation and its modes of production and absorption within the gas mixtures used in counters. Among the earliest of these (9) experiments was that of Greiner, who studied counters filled with oxygen, hydrogen, or air. The experiment consisted of mounting two counters inside the same envelope with their cylinders open to each other and their anodes separated by about

one centimeter. From measurements of the number of counts which spread from one counter to the other at different pressures, Greiner computed absorption coefficients for the different gases. To prove that the spreading was accomplished by the passage of ultraviolet radiation across the gap between the counters, he inserted light filters between the tubes. Only the thinnest nitrocellulose films, about twenty thousandths of a micron in thickness, which were transparent to ultraviolet radiation below 1000 A, permitted the discharge to spread from one tube to the other.

Greiner's experiment was performed with simple gases, in which the ultraviolet radiation regenerated Townsend avalanches by a cathode photoelectric effect. In another (10) version of this type of experiment, Ramsey showed that two counters would trigger each other in coincidence when filled with monatomic or diatomic gases, but that the introduction of a small amount of polyatomic admixture, caused the counters to fire at random with respect to each other. Furthermore, by plotting coincidence rate versus resolving time of the coincidence circuit, it was found that the photoemission was

9. E. Greiner, Z. Phys. 81, 543(1933).

10. W. E. Ramsey, Phys. Rev. 58, 476(1940)

confined to a period of approximately one microsecond, even though the pulse on the counter wire required from one to twenty microseconds to attain one half its peak amplitude.

The mean free path of the ultraviolet radiation responsible for spreading the discharge in counters with polyatomic constituents, has been evaluated by a number of experiments. <sup>(4)</sup> Stever obtained an interesting picture of the process by using divided cathodes and beaded anodes. In the latter type of counter, glass beads were sealed on to the wire at equal intervals along its length. From observations of pulse size it was established that the discharge jumped the obstacle of the glass bead only if the beads had less than a minimum diameter, or what is equivalent, if the ratio of field strength to pressure,  $E/p$ , exceeded a critical value. <sup>(11)</sup> Further studies showed that besides the obstructing effect of the glass bead for ultraviolet light, the field intensity was reduced about the glass bead. The photons were all absorbed in the immediate neighborhood of the bead where the field was too low to develop a complete avalanche.

Attempts to clarify the details of the emission and absorption processes have not been entirely successful. Alder <sup>(12)</sup>

11. M. H. Wilkening and W. R. Kanne, Phys. Rev. 62, 534(1942)
12. F. Alder, E. Beldinger, P. Huber, and F. Metzger, Helv. Phys. Acta 20, 73(1947)



and his coworkers recently performed a variation of the Greiner type of split counter experiment to determine the absorption coefficient of an alcohol vapor admixture for the ultraviolet photons emitted in the discharge. The two counters were mounted in a common envelope at a fixed separation of 11 centimeters. At first, the counters were filled with a mixture of simple gases, argon plus air, which gave satisfactory counting characteristics. With this filling, every count in one tube triggered the companion tube coincidentally. Contaminating the simple gas mixture with only a few tenths of a millimeter Hg of alcohol sufficed to reduce the number of spreading discharges to a vanishingly small figure. The absorption coefficient computed from this experiment was  $640 \text{ cm}^{-1}$  (at atmospheric pressure). With an admixture of 15 mm Hg of alcohol, the number of photons fell to  $1/e$  of its initial value in 0.8 mm. In obtaining this result it was assumed that introducing alcohol in these low concentrations did not affect the number of photons per discharge nearly so much as it did the absorption of photons.

Still another experiment of this type reported by  
(13)  
Liebson attempted to avoid the possibility of confusing a decrease in photon emission with an increase in absorption coefficient. All conditions of the discharge were held

13. S. H. Liebson, Phys. Rev. 72, 602 (1947)

constant and only the gas path which the photons were required to traverse was altered, by an expanding bellows connection between the counters. The magnitudes of the total absorption coefficients for the rare gases, with the alcohol or methylene bromide admixtures which he used, were comparable to those computed by Alder and his coworkers, but Liebson found that constant coefficients per unit pressure were obtained only if the absorption were attributed entirely to the rare gas.

The qualitative conclusion to be drawn from these experiments is that in gases containing polyatomic admixtures, the absorption of ultraviolet quanta by photo-ionization of the gas is very effective in confining the spreading mechanism to the immediate neighborhood of the wire. The ultraviolet radiation may be composed of a number of wavelengths some of which may reach the cathode and contribute a photoelectric effect. Experiments with split cathode counters, filled with the typical operating mixtures showed a small but measurable spreading of the discharge by ultraviolet radiation absorbed in the gas at distances of many centimeters, which could not

14. J. D. Craggs and A. A. Jaffe, Phys. Rev. 72, 784(1947)

15. C. Balakrishnan, J. D. Craggs and A. A. Jaffe, Phys. Rev. 74, 410(1948)

be attributed to the same photons which propagate the discharge along the wire. These less abundant photons were also capable of ejecting an appreciable number of cathode photoelectrons as part of the mechanism of spreading the discharge. In any combination of gas mixtures and cathode surfaces, it may be expected that all of these processes of photon emission and absorption in the gas and photoelectric emission at the cathode play a role, but their relative importance may differ considerably. There is a need for still more refined measurements of the production of photons and the cross-sections of photon absorption between 600A and 1200A before the Geiger counter mechanism can be quantitatively described.

If Alder's value of about one millimeter for the mean free path of the quanta is accepted, it is immediately apparent that the discharge in a counter with polyatomic admixture will spread with a smaller velocity than in a simple gas counter. The original avalanche will radiate quanta in all directions and breed new avalanches, whose number will fall exponentially with distance from the parent avalanche. The first generation of avalanches will initiate succeeding generations and the discharge will spread step-wise along the length of the wire, producing thousands of avalanches per centimeter. Since the duration of a single step can not be much less than  $10^{-8}$  seconds, the velocity of spread may be as slow as  $10^6$  to  $10^7$  centimeters per second.

The relation between the velocity of spread and the (16) overvoltage is almost linear. By lowering the noble gas pressure without altering the quenching gas pressure, the spread velocity is increased. This behavior could be explained by a decrease in the duration of a single avalanche because of increased electron mobility in the avalanche. The velocity of propagation furthermore depends on the nature of the noble gas, all other factors being constant. For example, the discharge spreads about three times as fast in helium as in argon. Here again the explanation may be in the higher electron mobility in helium compared to argon, which would be expected to decrease the duration of the individual avalanche.

#### Growth of the Pulse

Because of the enormously greater mobility of the electrons compared to the positive ions (about 1000/1), the positive ions at the wire move only a few thousandths of a cm. before the completion of the electron avalanche. As the discharge continues the positive ion space charge sheath builds up until the field strength near the wire is lowered beyond that required to maintain gas multiplication.

For small overvoltages, the charge generated per unit length of counter depends almost linearly on the over-

16. J. M. Hill and J. V. Dunworth, Nature 158, 833(1946)

voltage,  $V-V_s$ , which is the difference between operating voltage and threshold. At higher overvoltages the slope of the curve of charge per pulse versus overvoltage falls to about half its initial value. At a given overvoltage the charge per pulse is almost independent of the pressure and depends only on the geometry. These characteristics are illustrated by the curves of Fig. (5) for alcohol argon mixtures. The capacity of a typical counter ( $b = 1$  cm.,  $a = 0.01$  cm) supports a charge of about  $1.2 \times 10^{-13}$  coulombs per cm. of length per volt of potential difference. In most counters of average size the charge per pulse lies between  $10^{-11}$  and  $10^{-13}$  coulomb per cm. of length at threshold and may be 100 times as great at the end of the plateau.

The voltage pulse on the wire can be attributed entirely to the motion of the positive ions. The electrons are held on the wire by the image force field of the positive ions. Initially, with the sheath almost in contact with the wire, nearly all the electrons are bound to the wire. As the sheath expands radially, the image charge decreases and the electrons flow away from the anode, giving rise to a voltage pulse on the grid of the amplifier coupled to the wire of the counter. The rate of release of electrons at the wire of the counter. The rate of release of electrons at the wire depends on the rate of drift of the ion sheath which

in turn varies with the radius of the sheath. The radial velocity of the sheath is approximately proportional to the field or inversely proportional to the radial distance from the wire. At the start, the shape of the pulse is affected by the time required to propagate the discharge throughout the length of the tube. Since the discharge may spread at the rate of about 10 cms per microsecond in a self quenched counter, it may require of the order of a microsecond for the entire ion sheath to mature in a long counter during which time the voltage pulse can rise to a few tenths of its peak value (without differentiation). The rate of rise increases until the time at which the ion sheath is completed. After the sheath is completed the rate of rise of the pulse decreases. It may attain one half its peak value in one or two microseconds and thereafter increase very slowly. With infinite series resistance in the fundamental circuit (no RC differentiation), the pulse would reach its final and maximum value in the time required for the positive ion sheath to traverse the tube, about  $10^{-4}$  to  $10^{-3}$  seconds. Decreasing the series resistance, allows the applied potential to be restored on the wire in accordance with the time constant given by the product of the wire system capacity and the series resistance. The appearance of the differentiated pulse for different values of the series resistance is shown in Fig. (6).

### The Dead Time and Recovery Time

As the positive ion sheath moves outward towards the cathode the field near the wire returns to normal. The time required for the positive ions to reach the critical distance from the wire corresponding to threshold field defines the dead time of the counter. During this period the counter is insensitive to the passage of further ionizing particles. The additional time required for the ions to reach the cathode is called the "recovery time" and the size of any pulse occurring within this time is determined by the time elapsed since the initial discharge, a pulse at the end of the recovery time being of the same size as the initial pulse.

Fig. (7a,b) is a triggered sweep pattern of the type (5) first used by Stever to illustrate the deadtime and recovery time characteristics of a self-quenching tube. Following the trigger pulse, the sweep shows no pulses until the dead-time interval is passed, at which time small pulses begin to appear. These grow in amplitude with elapsed time from the triggering of the sweep. The envelope of these pulses traces the shape of the recovery curve of the electric field near the anode wire, as shown in Fig. (7c). From studies of the recovery curve it is possible to obtain considerable information about ion mobilities in different gases and at various field strengths. Many interesting observations have already been made.

For example, it is possible to identify the ions making up the sheath in mixtures of polyatomic gases, such as, for example, alcohol and methane, where the recovery time was found to be characteristic of the drift time of alcohol ions. In many gases the observed mobilities are identified with fragment ions rather than the parent molecules. The drift time of the ions in a hydrogen-alcohol mixture surprisingly enough was found to be longer than in oxygen-alcohol, indicating that the mobilities of these ions in the high fields of counters may be considerably different from those measured at small field strengths.

The deadtime and recovery time in a tube of ordinary dimensions are roughly equal to each other and of the order of a few hundred microseconds. The critical distance to which the ions must move before the field at the wire recovers to threshold is about half the counter radius. This critical radius,  $r_c$ , is related to the overvoltage  $V-V_s$ , the cylinder radius,  $b$ , and the charge  $q$ , per unit length of the ion sheath by

$$r_c = b e^{-\frac{V-V_s}{2q}} \quad (3)$$

The deadtime therefore decreases with increasing overvoltage, and is shorter in a tube of smaller dimensions and larger ratio of anode to cathode diameter. Deadtimes as short as 5

17. S. C. Curren and E. R. Roe, R.S.I., 18, 871(1947)

18. P. B. Weisz, J. Phys. & Colloid Chem. 52, 578(1948)



microseconds have been obtained in tubes having cathode and anode diameters of 0.25 inch and 0.15 inch respectively.

#### The Role of the Quenching Admixture

The treatment of the Geiger counter mechanism up to this point provides a picture of the growth of the discharge and the shape of the pulse. Upon the subsequent arrival of the positive ion sheath at the cathode, the electric field within the counter tube is fully restored. This introduces the possibility of rekindling the discharge by secondary electron emission. Suppose, for example, that the sheath consists of argon ions whose ionization potential is in excess of twice the work function of the cathode surface. An argon ion can first draw an electron out of the cathode and become neutralized. The energy difference between the ionized argon and the work function appears as recombination radiation with an energy in excess of the photoelectric threshold energy. The recombination photon can then eject an electron from the cathode and initiate a new avalanche. In a non-self quenching counter it is therefore necessary to quench the discharge by the use of either a large series resistance or an electronic quenching circuit, which prevent recovery of the threshold counting field until deionization of the gas is complete.

Self quenching counters are usually produced by admixing a small amount of polyatomic organic vapor to the non-self-quenching gas. Almost any molecule, inorganic as well as organic, containing

three or more atoms will contribute to the quenching mechanism. Self-quenched counters have been made with triatomic gases such as sulphur dioxide and nitrous oxide. Among the diatomic molecules, only the halogens have been found to quench properly. The primary requirement for quenching is that no excited or ionized molecules capable of inducing secondary emission shall reach the cathode surface. In a typical mixture of ten parts of argon to one of alcohol at a total pressure of 10 cms. Hg, an argon ion formed in the discharge must make about  $10^5$  collisions with gas molecules in traversing the anode to cathode distance. Because of this large number of collisions, the chances are very favorable for the transfer of ionization from argon ions to molecules of alcohol. Energetically, all that is required is that the ionization potential of the quenching gas be lower than that of argon. This condition is fulfilled by alcohol in argon and is satisfied by almost all polyatomic molecules in combination with helium, neon, or argon. The ionization potential usually decreases with increasing complexity of the molecule. In the experience of this laboratory alone, over thirty different admixtures were investigated which produced usable self-quenching counters. When krypton or xenon are the vehicular gases, their ionization potentials are lower than those of many of the commonly used quenching gases and it becomes much more difficult to select admixtures which satisfy the requirements of the transfer process.

19. H. Kallmann and B. Rosen, Zeits. f. Phys. 61, 61(1930)

In transferring ionization energy to the polyatomic molecule, the neutralized argon ion emits recombination radiation. This radiation may be absorbed by another polyatomic molecule which then photodissociates into two or more neutral molecules or radicals, with emission of still longer wavelength photons. The degradation of the original photon through many processes of this type amounts to a "red shift" of the photon spectrum beyond the photoelectric threshold of the cathode. The positive ions of the polyatomic molecules and dissociation fragment ions migrate out to the cathode where they are neutralized by drawing electrons out of the metal surface. After neutralization, the molecule is left in an excited state from which it may radiate a photon or predissociate without radiating. Radiation is very unlikely to occur because the lifetime against radiation is about  $10^{-8}$  second which is much greater than the time required for the neutralized atom to travel the remaining distance to the cathode. The quenching process can be completed successfully then if: (1) the excitation energy left with the neutralized molecule is less than the photoelectric threshold of the cathode, in which case no secondary electrons can be ejected; or (2) the excitation energy is dissipated in predissociation before the molecule collides with the metal wall.

It is possible that the first process, which requires the

ionization energy,  $E_i$ , of the quenching admixture<sup>to</sup> be less than twice the work function,  $\phi$ , of the metal cathode, may be largely responsible for the excellent quenching properties of the halogens and perhaps the halogenated hydrocarbons such as methylene bromide. In experiments conducted here, tubes filled with these admixtures were equipped with quartz windows but produced no photocathode response to the shortest U.V. transmitted by quartz, about 1850 angstroms or 6.5 ev. The cathodes used in these tubes were iron or copper, which in vacuum photocells are known to have work functions of 4 to 5 ev. However, it is also well known that in the presence of even the less active gases, the photoelectric threshold of these metals may be considerably shifted, so that it would not be surprising if the halogens were capable of increasing the threshold energies well beyond the limit of 6.5 ev. observed in the quartz window tubes. Since  $E_i$  of  $\text{Cl}_2$  is 13.2 ev and of  $\text{Br}_2$  is 12.8 ev, it is apparent that the condition for secondary emission,  $E_i > 2\phi$ , is not fulfilled.

The second process, in which the molecule predissociates before radiation, becomes more and more probable, the greater the complexity of the polyatomic molecule. Neutralization of  
(20)  
a polyatomic ion occurs by field emission which is effective

20. M. L. E. Oliphant and P. B. Moon, Proc. Roy. Soc. A  
127, 388(1930)

at a distance of about  $10^{-7}$  cms from a metal surface whose work function is about 4 or 5 ev. After neutralization, the excited molecule ( $E_{\text{exc}} = E_i - \phi$ ) must approach within about  $10^{-8}$  cms, of the surface before secondary electron (21) emission is possible. At the thermal velocities with which the positive ions approach the cathode,  $10^{-7}$  cms. is traversed in about  $10^{-12}$  seconds. To avoid secondary emission, the molecule must predissociate in less than  $10^{-12}$  seconds. The lifetime against predissociation in polyatomic molecules is closer to  $10^{-13}$  seconds, about the time of one interatomic vibration. Spectroscopically, this property of predissociation in polyatomic molecules can be detected by the appearance of continuous absorption at wavelengths equal to  $(E_i - \phi)$ . Using alcohol ( $E_i = 11.3$  ev) and copper ( $\phi = 4.0$  ev) for illustration, the difference  $(E_i - \phi)$  is 7.3 ev, which remains with the molecule as excitation energy, equivalent to absorption of a quantum of 1700A wavelength. The alcohol spectrum shows continuous absorption below 2000A accompanied by photodecomposition, indicating that the neutralized but excited molecules should predissociate in about  $10^{-13}$  second and satisfy the quenching requirement.

#### The Influence of Metastable Atoms

A metastable atom produced in the discharge remains

21. H. S. W. Massey, Proc. Camb. Phil. Soc. 26, 386(1930)

in that state until its energy is radiated or dissipated in a collision of the second kind. If the metastable atom, which is electrically neutral, drifts to the cathode wall the probability of ejecting an electron there may be as high as fifty percent. Although the average lifetime of metastable states in neon before radiation is about  $10^{-4}$  seconds, Paetow<sup>(22)</sup> found a measurable current caused by metastable atoms in neon persisting for as long as a second after terminating a discharge between parallel plates.

The highly purified rare gases taken by themselves, are unsuited for use in counters because their metastable states are so readily excited by electron impacts. Ejection of electrons by these metastables after the positive ion sheath has spread beyond the critical deadtime radius, reignites the discharge and leads to trains of multiple counts, or continuous discharge. A counter tube filled with rare gas is therefore unusable unless a foreign gas is admixed which de-excites the metastable atoms on colliding with them. Hydrogen is effective in quenching the metastable states of argon and neon and has been used with those rare gases to make permanent gas mixtures for non-self-quenching tubes.

22. H. Paetow, Zeits. f. Physik, 111, 770(1939)

The effect of mixing hydrogen with argon or neon on the performance of a counter operated with an external quenching circuit is illustrated by the plateau curves of Fig. (8). Less than ten percent of hydrogen in neon does not provide enough collisions between hydrogen atoms and metastable neon atoms to de-excite completely the metastables before they radiate or reach the cathode. Adding more than ten percent of  $H_2$  produces a plateau almost as long as is obtained in pure hydrogen. Argon requires a much greater admixture of hydrogen to produce a satisfactory plateau. The ionization energies,  $E_i$ , and metastable energies,  $E_m$ , listed in Table I show that it is energetically possible that metastable neon can be quenched by ionizing hydrogen, but that argon can be quenched only by exciting hydrogen ( $E_{exc} = 11.5$  ev.).

Much more striking effects attributable to the quench-  
(23)  
ing of metastable states were discovered by Penning and his coworkers in their studies of breakdown voltages,  $V_B$ , in rare gas discharges. Great differences appeared in the measured  $V_B$  which could only be attributed to minute traces of impurities. For example, baking a tube filled with pure Neon dropped its  $V_B$  by 100 volts, but a subsequent glow discharge treatment raised it again. A high frequency electrodeless

23. F. M. Penning, Zeits. f. Physik. 46, 335(1927)

TABLE I

Vehicular gas	Admix	$E_i$	pd	$V_B$	$V_B'$
Neon $E_m = 16.6$ ev	.02%K <sub>r</sub>	13.3	20	350	170
	.01H <sub>2</sub>	16.1	18	350	260
	.05H <sub>2</sub>	16.1	18	340	210
	.01N <sub>2</sub>	16-17	18	350	200
	.05N <sub>2</sub>	16-17	18	340	160
Argon $E_m = 11.6$ ev	.03K <sub>r</sub>	13.3	15	500	500
	.03Xe	11.5	14	520	530
	.05 CO <sub>2</sub>	15	14	460	470
	.05 CO <sub>2</sub>	14	14	480	500
	.05 NO	9	14	470	480

NO was the only exception to the rule that  $V_B$  is reduced if  $E_i < E_m$ . Penning suggested that the neutral NO molecule had many states above the ionization limit of 9 volts which were closer to the 11.6 ev of metastable argon, making excitation to those levels more probable than ionization.



discharge sometimes raised and sometimes lowered  $V_B$ .

Only after prolonged glow discharging, which is known to clean up many impurity gases, would  $V_B$  reach a stable upper value. By deliberately contaminating neon with traces of argon, mercury, and krypton in concentrations as low as 0.0001 percent, Penning obtained remarkable reductions in  $V_B$ .

It was impossible to explain these results by hypothesizing that since the admixed gas had a lower ionization potential than the main gas, it was therefore more readily ionized, resulting in a lowering of  $V_B$ . The relative contribution of the mercury admixture to ionization, for the case of Hg contamination in neon was computed to be about 0.0005, entirely too small to be significant. An explanation of the reduced  $V_B$ , based on the transfer of excitation energy of neon to ionization energy of the admixture was more plausible. In pure neon there is no mechanism for converting excitation energy to ionization, but neon atoms excited to metastable states in the discharge could have a relatively great efficiency for ionization of a trace admixture if the energy condition,  $E_m > E_i$ , is fulfilled. Many collisions are made during the life of the metastable atom and consequently the chance of an eventual collision with an admixture atom is great. To materially influence the breakdown voltage, these collisions

should occur within a few microseconds of the first avalanche. At the pressures ordinarily used in counter tubes a metastable atom may make between  $10^4$  and  $10^5$  molecular collisions per microsecond. A concentration of quenching admixture as low as  $10^{-4}$  to  $10^{-5}$  would therefore effectively remove almost all the metastable atoms within a few microseconds, if every collision between a metastable and an admixture molecule had a high probability of deexciting the metastable.

Fig. (9) and Table I summarize the results of Penning and his coworkers. The columns of Table I list:  $E_i$  the ionization potential of the admixture;  $pd$ , the product of pressure and distance between electrodes;  $V_B$  the breakdown voltage of the pure rare gas;  $V_B'$ , the breakdown voltage with the admixed impurity gases. The most pronounced effects were obtained with an admixture of argon in neon where as little as 0.005 percent argon in 112 mm Hg of neon reduced the striking voltage from 770 volts to 185 volts between parallel plates, 7.5 millimeters apart, (Fig. 9C).

#### Low Voltage Counters

The condition that  $E_m$  of the rare gas atoms be higher than  $E_i$  of the admixture is satisfied by a great many of the polyatomic quenching gases commonly used in counters. The

tendency to reduce the striking voltage by converting metastable energy to ionization energy, however, is opposed by the tendency toward inelastic electron impacts with the polyatomic molecules. These impacts keep the electron energies below  $E_m$  and  $E_i$  of the rare gas and suppress the growth of Townsend avalanches, thereby raising the threshold voltage requirement. In normal counter mixtures, the concentration of polyatomic constituent needed to quench adequately the discharge and produce a satisfactory life is so high, that the process of holding down the distribution of electron energies in the avalanche through inelastic impacts with polyatomic molecules, is more important than the ionization of metastables. The most notable exception observed here thus far was methylene bromide in argon, where the amount of admixture could be reduced to a few tenths of a percent without destroying the quenching properties of the mixture. Such tubes, operating at 250 volts, exhibited plateaus about 100 volts long and had useful lives of  $10^7$  counts. Weisz observed the effect of diluting hydrocarbon admixtures in argon to very low concentrations. The threshold voltage was markedly reduced in every case satisfying  $E_m > E_i$ , although no examples were observed which promised practical usefulness in the sense of

satisfactory plateaus and long counting life.

Recent attempts to produce low voltage thresholds in counters, with the neon-argon mixture and others described in Table I above, have been very successful. Previously the lowest operating voltages had been obtained by reducing the gas pressure, decreasing the anode and cathode radii, or introducing a grid. None of these techniques produced low voltage thresholds without sacrificing other desirable features such as high efficiency and fast recovery times.

The theory of operation of counters filled with permanent gases having high threshold voltages and utilizing electronic quenching, applies equally well to mixtures of the Ne-A (25) type with their characteristically low values of  $V_B$ . Simpson prepared counters filled with 5 cms. Hg of neon and 0.01 percent argon, which operated in a Neher Harper quenching circuit with thresholds at 120-135 volts. Self-quenching counters having low threshold voltages were prepared by adding fractions of a mm. Hg pressure of polyatomic vapors to the neon-argon mixture. At the lowest threshold voltages, obtained by using the minimum amounts of vapor, such counters were temperature sensitive, short-lived, and required some electronic circuitry to assist the quenching. Using somewhat higher, pressures, i.e., 1 mm Hg. of ethylacetate and 50 cms. Hg of

25. J. A. Simpson, MDDC Report 870, Declassified 1947.

Ne-A, fast counters were made in this Laboratory with thresholds of 350 volts and plateaus of 100-150 volts. These counters had useful lives of about  $10^7$  counts.

Counters employing traces of the halogen gases with  
(26)  
neon or argon, have low threshold voltages combined with many other desirable properties. They cannot be damaged by excessive counting rates or running over the upper voltage limit of the plateau. When chlorine or bromine is used, the tubes are insensitive to temperature variations over a wide range. As was indicated in Penning's experiments, a halogen admixture is also capable of reducing the corona breakdown voltage, when the energetic requirement,  $E_i < E_m$ , is satisfied. Fig. (9) shows that a trace of iodine ( $E_i = 9.7$  ev), in argon ( $E_m = 11.6$  ev) was as effective in reducing  $V_B$  as was Hg. In a similar manner, chlorine ( $E_i = 13.8$  ev) and bromine ( $E_i = 12.8$  ev) should ionize metastables in neon ( $E_m = 15.6$  ev). At higher concentrations of halogen admixture, the halogen acts predominantly as an electron trap and raises the breakdown voltage. As the halogen concentration is reduced however, ionization of the halogen molecules upon impact with metastable rare gas atoms becomes more probable than electron attachment and the starting voltage is lowered. Fortunately, relatively small

26. S. H. Liebson and H. Friedman, R.S.I., 19, 303(1948)

concentrations of halogen are required to satisfy all the Geiger  
(27)  
counter quenching requirements. It has been pointed out that,  
in theory, the halogens possess the properties required in quench-  
ing that are otherwise found only in poly-atomic molecules.

A major difficulty in the use of halogen admixtures is the  
clean-up of the small amount of halogen originally present, by chem-  
ical reactions within the tube. Tubes constructed with electrodes  
of brass, copper, silver, aquadag and various plated surfaces, failed  
very quickly when filled with a rare gas plus a halogen admixture.  
Satisfactory results have thus far been obtained with the use of  
tantalum and of chrome-iron, and bromine appears to be much less re-  
active than chlorine. If the efficiency of the counter for ionizing  
events need not be greater than 90 percent, higher concentrations of  
the halogens may be used and a slow clean-up then produces a cor-  
respondingly slower deterioration. The inefficiency and operating  
voltage both rise rapidly with increasing halogen admixture, however,  
and it is much more desirable to seek to eliminate the chemical clean-  
up process from the beginning, rather than to resort to higher concen-  
trations of the halogen.

The pulse characteristics in low voltage counters differ only  
to a minor degree from those of the more common

(27) R. D. Present, Phys. Rev. 72, 243(1947)

higher voltage counters. The lower the operating voltages, the longer is the rise time of the pulse. At the lowest voltages, the time to reach peak amplitude may be ten times as long as in similar "high" voltage counters. The charge per pulse is also considerably greater. Deadtimes are not appreciably different and generally center about 200 microseconds for tubes of ordinary dimensions.

#### The Plateau Characteristic and Spurious Counts

The plateau of a Geiger counter may be defined as the voltage range over which the counting rate at a constant intensity of irradiation is substantially independent of voltage. If the "counting range" is taken to mean the difference in voltage between threshold and the inception of a self-sustained corona discharge, then the plateau is always much shorter than the counting range. No Geiger counter exhibits an ideally flat plateau characteristic for any considerable range above the threshold voltage. An increase in counting rate with overvoltage is always observed which may be as high as 0.1 percent per volt in counters that are still considered satisfactory for many applications.

A portion of the slope can be attributed to a real increase in sensitivity, but the remainder arises from increasing numbers of spurious counts at high over-voltages. The former effect is largely explained as an increase in volume

of the counter through the growth of the electrostatic field at its ends. Of course, any misalignment of the electrodes, such as the wire being cocked at an angle to the axis of the cylinder, will increase the sensitivity with increasing overvoltage by causing different portions of the counter to exhibit different threshold voltages. Finally, any inefficiency from failure to mature a complete discharge would be lessened by an increase in overvoltage, since the number of photons per discharge increases with overvoltage and improves the probability of spreading the discharge completely. The electrostatic effects can be minimized in general by carefully aligning the electrodes, making the length to diameter ratio as large as convenient, polishing the anode to remove sharp points, and shielding the ends of the wire with insulating sleeves so as to limit the expansion of the sensitive volume beyond the ends of the cylinder. In the preparation of most counters, these precautions are more or less routine, so that spurious pulses generated by the discharge itself are usually the major contributors to plateau slope.

The most serious source of plateau slope in Geiger counters is a type of spurious counts that appear in the form of "after-discharges" or trains of counts following a valid count. In some counters these multiples appear almost



immediately above threshold; in all counters they appear at sufficiently high overvoltages. The voltage region in which these trains of multiple counts begin to appear in appreciable numbers marks the limit of the useful plateau range. Certain fillings, such as argon and alcohol, which show no spurious pulses at overvoltages of 100 to 200 volts, produce very flat plateaus. If the argon is of spectroscopic purity (99.9%) and the alcohol is free of air and water, a plateau slope less than 0.01 percent per volt may be obtained. A commercial grade of argon (98%) on the other hand, produced slopes from 0.05 to 0.15 percent per (28) volt, and contamination with air increased the slopes proportionately. An optimum concentration of quenching admixture was also observed which was about 5 percent for alcohol. Larger concentrations increased the slope. This behavior could be explained by failure of an increased number of discharges to develop fully because of the suppression of photon emission in the avalanches. Twenty percent of alcohol in argon increased the slope to 0.05 percent per volt. The behavior of alcohol-argon is also typical of helium and neon and many of the more commonly used hydrocarbon quenching admixtures, such as ether, ethyl acetate, amyl acetate, and (17) ethylene. In contrast, many spurious counts were observed when alcohol was used with  $O_2$ ,  $N_2$ , or  $H_2$ . For a mixture of hydrogen and alcohol, 27 percent of the counts

(28) S. A. Korff, W. B. Spartz, J. A. Simpson - MDDC Report 1704.

observed in the middle of the plateau were spurious; in oxygen and alcohol the fraction of spurious counts was 10 percent.

Although a counter may initially exhibit a very flat plateau, the slope invariably increases with use. The rate at which this proceeds initially and over longer periods of use, varies with the particular gas mixture. In argon, with alcohol admixture, the slope may increase considerably at first, then remain relatively unchanged for a major portion of the useful life and finally deteriorate very rapidly. Some mixtures show a tendency to recover when not in use. All these effects reflect the contamination of the gas mixture by decomposition products of the discharge and the correlated loss of the optimum concentration of quenching constituent.

The process responsible for the major portion of the spurious pulses observed in counter tubes is positive ion bombardment of the cathode. As the overvoltage is raised, the number of positive ions per discharge increases. Since the emission of secondary electrons is directly proportional to the number of ions arriving at the cathode, the number of spurious counts should increase with overvoltage. Because of the well defined time required for the positive ion sheath to traverse the interelectrode space, spurious pulses arising from secondary emission are readily recognized. On an

oscilloscope screen, trains of spurious pulses at high overvoltage have the appearance of relaxation oscillations. The successive pulses in a train are uniformly spaced in accordance with the nature and pressure of the vehicular gas and the overvoltage, as predicted by the dependence of ion mobility on pressure and field strength. Figs. (10, 11, 12) illustrate: the increasing length of the trains of multiple pulses with increasing overvoltage or decreasing concentration of quenching admixture; the increase in spacing of multiples as the mobility of the positive ions is reduced by increased pressure; the dependence of the mobility, as reflected by the spacing of pulses, on the collision cross-sections of the rare gas atoms. Before arriving at the condition of continuous corona discharge, the number of pulses in individual trains may reach thousands without destroying the perfect spacing between pulses.

The ideas behind most procedures for treating counter tubes prior to filling, is to produce a high work function at the cathode surface and thereby reduce spurious pulses due to secondary emission. In many instances the effect of adsorbed polyatomic molecules on the metal surface is to increase its work function more markedly than most of the treatments to oxidize or make the surface passive which have so often been recommended in the literature. Measurements of the

photosensitivity of an alcohol-argon counter with a clean copper cathode show that the photoelectric threshold is depressed toward the ultraviolet as more alcohol is admixed with the argon. During use, the discharge decomposes the alcohol and the threshold climbs steadily back toward the visible. When using low work function electrode materials such as aluminum or magnesium, the work function must be considerably increased by chemical treatment or by deposition of a very thin layer of a more suitable surface such as copper, before satisfactory counting can be obtained. Glow discharging in an active gas, before filling, is often effective in subsequently preventing spurious counts. Several more extreme treatments have been described such as mechanically coating the cathode with a very thin layer of a high work function surface, for example, a coating of lacquer. The influence of such a coating can be judged from its effect on the photoelectric threshold. Because the lower energy photoelectrons released at threshold cannot penetrate the thin coating, the photoelectric limit appears to be shifted toward the ultraviolet.

A less important class of spurious counts are those attributable to the charging of particles or thin layers of insulating material on the cathode. During the discharge, positive ions may remain bound to these insulating surfaces, or the particles may acquire charge as a result of photoelectric

emission. Subsequently, spurious counts may be triggered by electrons released in the neighborhood of these charged spots. Experiments with plane parallel electrodes (29) demonstrated the presence of an electron current decreasing roughly exponentially with time, following the termination of a glow discharge. A measurable current was observed for fully 15 minutes with nickel electrodes coated with colloidal graphite and magnesium oxide. After prolonged baking to remove the oxide, this after-discharge current almost entirely disappeared. The effect of irradiation (30) was demonstrated by an experiment in which parts of a counter tube were exposed to intense x-rays and the counter subsequently reassembled. A much higher background was then observed, which decayed slowly with time. Many counters go over into an unbroken chain of counts when the over-voltage exceeds the limit of the plateau and do not recover when returned to what was previously normal operating voltage. The applied voltage must then be dropped below threshold for at least a few seconds before such tubes recover. This general behavior closely resembles the phenomena observed in the aforementioned experiments with MgO coatings and irradiated electrodes.

29. A. Guntherschulze, A. Physik 86, 778(1933)

30. Roggen and Scherrer, Helv. Phys. Acta 15, 497(1942)

### Life of Self-Quenching Counters

Most self-quenching counters exhibit similar symptoms of ageing. The threshold voltage rises, the plateau slope increases, and multiple pulses appear at progressively lower voltages. Many tubes become increasingly photosensitive. Some counters may be brought into self-sustained discharge above the plateau, yet recover immediately when returned to operating voltage, whereas others are permanently destroyed if brought into continuous discharge even momentarily. Most of these observations are understandable in terms of the decomposition of the quenching admixture in the course of the discharge. A typical counter initially contains approximately  $10^{20}$  polyatomic molecules. About  $10^{10}$  of these molecules are ionized in each discharge and dissociate when they reach the cathode wall. It seems necessary therefore to accept an upper limit of about  $10^{10}$  counts for the maximum life of a self-quenching Geiger counter containing polyatomic molecules. A simple demonstration of the breakdown of the polyatomic constituent is obtained by attaching a sensitive manometer to a counter tube under life test. The increase in total pressure contributed by the partial pressures of the end products of the discharge is readily observed. It is now believed that the ageing may generally be attributed to a combination of two

processes: (1) an alteration in the optimum gas composition resulting from decomposition of the quenching vapor; (2) the deposition on the electrodes of polymerization products manufactured as a result of the discharge. The former process is sufficient to account for most of the deterioration of ethyl alcohol and ethyl acetate fillings. The latter process has been identified with the short-lived performance of methane fillings.

The primary decomposition products are neutral radicals and fragment ions. Mass spectrometer research in recent years has revealed an abundance of fragment ions formed in electron bombardment of complex molecules, compared to the number of ions of the parent molecules. In some molecules such as tetramethyl lead <sup>(18)</sup> the parent ion is not observed at all. Some of the dissociated fragments may combine to form other organic molecules, which may or may not be quenching molecules. It may be reasoned that starting with a large molecule a relatively greater portion of the products of the discharge may again have quenching properties. This seems to be generally true. The lifetime of a counter using amyl acetate, for example, is about ten times as long as that obtained with ethyl alcohol admixture. Eventually, all the larger molecules must be broken down into the lighter fractions including

31. S. S. Friedland, Phys. Rev. 74, 898(1948)

non-self quenching gases such as hydrogen and oxygen.

In the case of methans, tubes are found to fail at between  $10^7$  and  $10^8$  counts, which is insufficient to account for decomposition of enough of the original admixture to spoil the tube. It has been shown (32) that the decomposition of methane yields hydrogen along with saturated and unsaturated hydrocarbons, and a deposit on the cathode cylinder which can be identified as a polymerization product formed from the unsaturated hydrocarbons. This polymerization process is known to occur quite readily in an electrical discharge at the surface of a metal electrode. The failure of counters using propane and butane also appears to be traceable largely to the deposition of dielectric polymers on the cathode surface. Such tubes cannot be restored to operation by refilling with a fresh gas mixture, unless the electrodes are washed with a solvent capable of removing the deposits.

#### Short Time Delays in the Firing of Geiger Counters

Coincidence counting is one of the most powerful tools available for the analysis of nuclear disintegration schemes and cosmic ray phenomena. In all cases, it is advantageous to reduce the coincidence resolving time to as short an interval as possible, if merely to reduce the number of accidental coincidences which statistically occur in direct proportion

32. E. C. Farmer and S. C. Brown, Phys. Rev. 72, 902(1948)



to the resolving time. In determining the decay scheme of a nucleus which undergoes a series of radioactive transitions in rapid succession, observations of delayed coincidences can reveal the time relationships in the chain of nuclear radiations. If two transitions follow each other in less than  $10^{-8}$  second, it is experimentally impossible to distinguish the spacing between them with Geiger counters.

If, however, the second transition in a sequence follows the first after an average time interval greater than  $10^{-8}$  seconds, it becomes possible to detect the deviation from simultaneity by delaying the count produced by the first transition long enough to bring it into coincidence with the second. To apply this type of measurement to timing events separated by as little as tenths of a microsecond requires experimental resolution times of a few hundredths of a microsecond. In attempting to decrease the resolving time much below a microsecond, however, many experimenters found inherent uncertainties in the firing times of counters of the order of a tenth of a microsecond, (33) which were entirely distinct from the occasional longer delays of 10 to 100 microseconds resulting from electron attachment to form negative ions.

The maximum resolution achieved with any coincidence arrangement using a pair of Geiger counters depends on the

33. C. W. Sherwin, R. S. I., 19, 111(1948)

rate of growth of the pulse in each counter following the passage of the ionizing photon or particle. Experimentally, it is observed that even when a pair of counters of average dimensions are fired by the same high speed particle there occurs a relative randomness in firing times with an average difference of as much as 0.2 microseconds. Short time delays in firing of a counter may be attributed to two sources:

(1) the electron transit time in the avalanche; (2) the time required to develop the initial part of the ion sheath after the first electron avalanche reaches the wire. The former delay arising from electron transit time is essentially independent of overvoltage, whereas the latter delay, involving growth of the ion sheath, decreases with increasing overvoltage. As was mentioned earlier, the elementary process of avalanche production beginning at a distance of a few wire diameters from the anode, requires about  $10^{-9}$  seconds. The collection time for the triggering electron and single Townsend avalanche which it creates, will obviously depend on the radial distance at which the primary electron is produced. To compute this time it is necessary to know the velocity of the electron at all distances from the wire. However, since an electron starting at the cathode must traverse the first half of the radial distance to the wire at nearly thermal velocities, its motion in the outer  $r/2$  portion of its path accounts for

almost all of the collection time. The average energy acquired per mean free path over the first half radius from the cathode is about  $1/4$  ev, which corresponds to an average velocity of about  $3 \times 10^7$  cms/sec. The maximum possible transit time in a tube of one centimeter radius will therefore be somewhat greater than  $3 \times 10^{-8}$  seconds. (34)

For an electron starting at intermediate radial distances, the transit time is roughly proportional to the square of the distance. In counters of larger diameters, transit times can therefore reach values in excess of a microsecond. (35)

Measurements on a tube 7 cms. in diameter revealed transit time delays of 0.3 to 2 microseconds.

The portion of the delay attributable to the rate of growth of the ion sheath depends on the sensitivity of the detector amplifier, the position along the length of the tube at which the sheath starts to develop, and the over-voltage. During the first tenth of a microsecond required for the sheath to spread a distance of a few millimeters, the rate of rise of the pulse on the wire may be less than one volt per tenth of a microsecond. Obviously, a wide band, high sensitivity amplifier would be required to detect the

34. S. A. Korff, Phys. Rev. 72, 477(1947)

35. H. Den Hartog, F. A. Muller, and N. F. Verster, Physica 13, 25(1947)

pulse within this time interval. The rate of rise increases rapidly after the first  $10^{-7}$  second, depending somewhat on whether the counter is triggered at the center or near one end. At the center, the discharge may spread in both directions whereas, at either end of the tube, the discharge can propagate only in the direction of the opposite end. The slope of the pulse during the spread of the discharge is roughly twice as steep in the former case. The behavior with change in overvoltage is also readily understandable, since the discharge is matured by photon emission and absorption and the abundance of photons per avalanche increases with higher overvoltage.

It is clearly indicated then, what steps may be taken to achieve the fastest possible coincidence resolving times. The smallest diameters and lowest filling pressures consistent with other experimental requirements should be selected to minimize transit time fluctuations. A sensitive wide band amplifier and operation at high overvoltage will make it possible to detect the pulse in the earliest stage of its growth. Resolving times as low as 0.035 microseconds without coincidence losses due to random time delays were (36) obtained in experiments by Mandeville and Scherb, with argon-ethyl ether fillings and a fast coincidence circuit.

36. C. E. Mandeville and M. V. Scherb, Nucleonics 3,2(1948).

## Cosmic Ray Efficiency

In the majority of Geiger counter tube types it may be safely assumed that a single ion pair formed anywhere within the volume of the Geiger counter will trigger a discharge. In detecting the passage of an ionizing particle such as a cosmic ray meson, the efficiency can ordinarily be made greater than 99.5 percent, by selecting a heavy gas and filling to a relatively high pressure. The rare gases, except for helium, yield many ions per centimeter of path when traversed by a high speed cosmic ray particle. The values of the specific ionization (ions per cm. per atmosphere) in neon, argon, and xenon are 12, 29, and 44 respectively, but the values for helium and hydrogen are no greater than about 6. Since the number of ions produced per centimeter of path fluctuates statistically, there is always a chance that the particle may traverse the counter without producing an ion pair. The average number of electrons,  $\bar{N}$ , left behind by a meson if it traverses a path length,  $d$ , in the counter is  $n p d$ , where  $n$  is the specific ionization and  $p$ , the fraction of atmospheric pressure. The probability of not producing an electron is therefore  $e^{-N}$  and the efficiency  $E$  is given by  $E = 1 - e^{-N}$ . For example, where the gas in the counter is argon at  $\frac{1}{10}$  atmospheric pressure, and the track length through the tube is 2 cms, 6 ions per meson are produced on the average, and the efficiency is 99.8 percent. If, now, the particle penetrates the counter close to the wall,

(37) J. C. Street and R. H. Woodward, Phys. Rev. 46,1029 (1934)

(38) M. E. Rose and W. E. Ramsey, Phys. Rev. 59,616 (1941)

traversing about  $1/6$  centimeter,  $N$  becomes equal to 1 and the efficiency is only 63 percent. In the same way, one finds that the efficiency for small counters and for counters filled with hydrogen or helium is considerably lower. For 90 percent efficiency in a 2 cm path, it is necessary to use about 15 cms Hg pressure of hydrogen or helium as compared to 3 of argon.

In certain cosmic ray experiments, low efficiencies are deliberately sought so as to distinguish for example between heavily ionizing mesons and electrons. Counters are prepared for such experiments by filling with a low pressure of hydrogen or with three or four cms of helium to which is added the minimum amount of a light polyatomic vapor sufficient to produce a self-quenching counter with a useable plateau.

There is another type of inefficiency associated with  
(37)  
electron attachment which was first demonstrated in studies of coincidence counting, with cosmic ray telescope arrangements. In the region near the cathode, the combined effects of low field strength and production of relatively few ion pairs makes electron capture to form negative ions sufficiently probable to have a marked effect on efficiency. The heavy negative ions drift slowly into the high field region where the negative charge may detach and initiate a delayed discharge, or the ion may retain its charge and not produce an avalanche at all. By varying the re-  
(38)  
solving time, of the coincidence circuit used with

37. J. C. Street and R. E. Woodward, Phys. Rev. 46, 1029(1934)

38. M. E. Rose and W. E. Ramsey, Phys. Rev. 59, 616(1941)

an oxygen filled counter from 0.2 to 70 microseconds, the efficiency of coincidence counting was altered from 50 to 80 percent. When the oxygen was diluted to 6 percent of an oxygen-argon mixture, the efficiency remained about 96 percent from 0.2 to 600 microseconds. The portion of the inefficiency which disappeared with increasing resolving time represented delayed counts originating from negative ions which gave up their electrons near the wire from 10 to 100 microseconds after their attachment. The inefficiency which is unaffected by resolving time represents the fraction of primary ionizing events which do not mature into counts. Although this inefficiency is only barely detectable in argon plus 6 percent oxygen, it is very pronounced in tubes containing admixtures of the halogens, halogenated hydrocarbons, ammonia, or sulphur dioxide. Fig. (13) shows the response to a collimated beam of x-rays passing axially down an end window counter tube at various radial distances from the cathode (39). With a filling of argon plus methylene bromide admixture, the efficiency decreased from close to one hundred percent near the wire, to only a few percent at the cathode. Exposed to cosmic rays, this tube showed an over-all efficiency of about 15 percent. Corresponding measurements are shown for chlorine and argon.

#### Soft X-Ray Counters

A counter tube for detection of soft x-rays can be designed so as to produce a count for virtually every quantum which enters the

(39) H. Friedman and L. S. Birks, R.S.I. 19,323(1948)

tube. In early work with x-ray counters, relatively low pressures of filling gases were used and ionization of the gas played a minor role in triggering the counters. The x-ray beam was usually directed at the cathode cylinder and released photoelectrons which initiated the counts. The x-ray photoelectric yield of any element reaches a maximum on the short wavelength side of its x-ray critical absorption limit. For wavelengths longer than those associated with the critical absorption the absorber is relatively transparent, yielding few photoelectrons. By selecting as cathode, a material whose K absorption limit fell at a slightly longer wavelength than the radiation being measured, it was possible to detect about fifteen percent of the quanta which struck the cathode, as <sup>(40)</sup> in the case of a zirconium cathode used to measure x-rays generated at 30 Kev ( $\lambda_{\text{max.}} = 0.6\text{\AA}$ ).

The form of counter tube best suited to the measurement of soft x-ray beams is the end window type, filled with a gas capable of absorbing a large fraction of the radiation admitted in the direction of the axis of the tube. The absorption of x-rays of wavelengths softer than 0.5 angstrom is almost entirely a photoelectric process in heavy gases such as argon, krypton, and xenon. It is therefore permissible to assume that the percentage of an x-ray beam absorbed in the counter tube gas represents the quantum counting efficiency, provided that each ejected photoelectron triggers a discharge. If

(40) H. M. Sullivan, R.S.I. 11, 356(1940)



argon is the vehicular gas, it strongly absorbs the K series radiations of elements up to about Zn(30). Krypton (36), whose critical x-ray absorption falls at 0.9 angstroms, is an efficient absorber of wavelengths shorter than this limit, and also matches the absorption in argon at the longer wavelengths. Xenon (54) absorbs strongly throughout this entire region of the spectrum. Fig. (15) illustrates the absorption characteristics of these three gases in the wavelength range from 0.4 to 2.4 angstroms. (39) It is apparent, that efficiencies approaching 100 percent are attainable over a large portion of this spectral range, if the proper gas is used at sufficiently high pressure or if a long enough gas path is provided to absorb the x-ray beam.

The most transparent, yet vacuum tight, windows for x-ray counters are in-blown glass bubbles, mica, beryllium, and Lindemann glass (consisting mainly of lithium tetraborate). Glass bubble windows of thicknesses between  $0.5 \text{ mg/cm}^2$  and  $1.0 \text{ mg/cm}^2$ , with apertures 2 cms. in diameter, are strong enough to support atmospheric pressure on the concave side and still transmit 1000 e.v. x-rays. Table II indicates the x-ray transparencies of mica, beryllium, and Lindemann glass at a few wavelengths in the soft x-ray region.

TABLE II

<u>Window</u>	<u>Transmission (percent)</u>		
	<u>GrK X(2.27A)</u>	<u>FeK X(1.94A)</u>	<u>CuK X(1.54A)</u>
0.020" Lindemann	4.5	14	38
0.010" "	22	37	61
0.001 Aluminum	37	53	71
0.001 Mica	40	56	74
0.0005 "	64	75	86
0.020 Beryllium	65	76	86

---

At MoK X(.7A), all the windows listed above transmit in excess of 90 percent of the x-rays.

---

Typical tube constructions are illustrated in Fig. (15). With glass or mica windows the active counting region can be brought up close to the window. Beryllium and aluminum windows are highly transparent but introduce the difficulty of insulating the window from the cathode, or retracting the anode to eliminate discharging to the window. The resultant dead space immediately behind the window, somewhat reduces the efficiency of the counter.

A beryllium window is particularly useful when it is necessary to measure soft x-rays in the presence of beta rays. For example, 5 year  $\text{Fe}^{55}$  decays by K electron capture into  $\text{Mn}^{55}$  which then emits 5.9 Kev x-rays.  $\text{Fe}^{59}$  has a 47 day half life and emits beta rays

with a maximum energy of 0.46 Mev and hard gamma rays. An argon counter with a beryllium window, 0.4 mm thick, detects about 50 percent of the soft x-rays, of  $\text{Fe}^{55}$  but less than 2 percent of the  $\text{Fe}^{59}$  betas. The ratio of sensitivities can then be inverted by using a thin mica window and helium, which will respond to every beta particle entering the tube, but cannot absorb the x-rays.

## Gamma Ray Counters

As the frequency of the electromagnetic radiation increases beyond the soft x-ray region, the photoelectric absorption in the gas assumes an insignificant role. Most gases used in counter tubes do not appreciably absorb photons whose energies exceed sixty or seventy thousand electron volts, and direct ionization of the gas is negligibly small. Hard x-rays or gamma rays are detected by virtue of the ionization of the counter gas by secondary photoelectrons, Compton recoil electrons, and electron-positron pairs produced within the cathode material. For the lighter elements and higher frequencies of gamma rays, the absorption is almost entirely the result of Compton scattering. At the other extreme of higher atomic numbers and softer radiation, photoelectric absorption becomes most important. Electron-positron pairs do not appear below 1.02 Mev., the sum of the mass energies of the two particles. The cross-section for pair production increases slowly with the excess of energy above this threshold and is proportional to atomic number. The photoelectric absorption coefficient is approximately proportional to the cube of the atomic number and decreases rapidly with increasing frequency. At 1 Mev, the photoelectric absorption coefficient in copper is already reduced to roughly 2 percent of the Compton scattering coefficient. In the very heavy elements, however, the photoelectric effect remains relatively important up to much higher energies. At 2.6 Mev, the photoeffect in lead is still about 15 percent of the Compton scattering. Pair production becomes comparable to Compton effect at much higher energies. In lead, gamma rays of 5 Mev produce about one positron for every three Compton recoil electrons. The same ratio

is reached in copper at closer to 10 Mev and in aluminum at about 15 Mev. The combined effect of all three processes contributing secondary electrons, is to make the counting efficiency roughly proportional to gamma ray energy, if the counter is constructed of a light-element such as copper. Cathodes of heavier elements, lead, bismuth, or gold, raise the efficiencies to a pronounced degree at both the low and high energy extremes.

In many nuclear experiments such as the determination of reaction yields, it is necessary to know the absolute counting efficiency at particular wavelengths. In order to compute what percentage of gamma ray quanta of a given energy incident on a Geiger counter will trigger counts, it is essential to understand how the number of secondaries injected into the gas of the counter depends upon the thickness and material of the cathode. If, for example the thickness of the cathode wall is much less than the range of the secondaries, almost all the secondaries will enter the gas and produce counts, but by the same token the fraction of the primary beam converted to secondaries will be small. On the other hand, when the thickness is much greater than the range of the secondaries, the absorption of primary radiation may be relatively great, but the secondaries produced at depths from the inner wall surface, greater than the maximum recoil electron range, cannot emerge to contribute counts. This behavior is illustrated in fig (16), computed for 2 Mev gamma rays entering aluminum. An optimum thickness exists, which produces the maximum number of secondaries per primary quantum. This thickness is of the order of the maximum range of the secondaries in the cathode material.

The Compton electrons exhibit a roughly exponential absorption as a consequence of multiple scattering and the dependence of recoil energy on angle. Let an absorption coefficient  $\mu_2$  be assigned to the recoil electrons, and let  $\mu_1$  represent the linear absorption coefficient for gamma rays. It then can be shown that for cathode thicknesses equal to or greater than the optimum, the ratio, R of the number of secondaries emerging from the cathode, to the number of primary quanta transmitted, is approximately

$$R = \frac{\mu_1}{\mu_2 - \mu_1} \quad (5)$$

This ratio is very nearly the efficiency of the counter. For example, a 2 Mev gamma ray, whose absorption coefficient in Al is about 0.12, produces Compton recoil electrons having an absorption coefficient of about 20. The efficiency, according to (5) should be about 0.6 percent. At 1.0 Mev,  $\mu_1$  is 0.17 and  $\mu_2$  about 55, which should reduce the efficiency to about 0.3 percent. It is approximately true for lighter elements such as Al and Cu, that the efficiency in the gamma ray region from 0.2 to 3 Mev is proportional to the energy and increases at the rate of about one percent per Mev.

(41)

The wavelength dependence of the contributions to counting efficiency for each of the three absorption processes is shown in Fig (17) for a copper cathode. The major contribution to the efficiency comes from Compton scattering. When the cathode is made of a heavier element, the efficiency is higher because of the more important contributions from photoelectric absorption and pair production. Fig. (17) also shows the total efficiency curve for lead. Since the Compton effect is independent of atomic number, the difference

(41) H. Bradt, P. C. Gugelot, O. Huber, H. Medicus, P. Preiswerk, P. Scherrer, Helvetica Physica Acta 19,77 (1946)

between the Pb and Cu curves represents the enhanced photoelectric contribution at lower frequencies and pair production at higher frequencies,

Considerable numbers of Geiger counter survey instruments are being used to monitor radioactive contaminations in atomic energy activities and x-ray laboratories, and in many cases the meter readings are calibrated in roentgens. It is interesting to apply some of the above data on efficiency to the problem of the ratio of counting rate to roentgen dose at various wavelengths. If, for example, the counting rate per milliroentgen per hour is assumed to be 100 cps at 1 Mev, then a copper cathode counter will deliver about 135 cps and a lead counter 106 cps at 2 Mev. for the same dose. This ratio of counts to roentgens has a minimum somewhere between 0.1 Mev and 0.5 Mev. On the low frequency side of the minimum the counting rate and roentgen dosage rate diverge widely.

(42)

Several years ago, Trost attempted to apply counters to roentgen dose measurements under 0.5 Mev <sup>in</sup> connection with stray radiation from x-ray apparatus. Using a typical metal-in-glass counter tube, he found it possible to keep the ratio of counts to roentgens constant within 12 percent between 60 and 120 KV. When a filter combination consisting of 1 mm of tin plus 1 mm of brass was interposed between the source and the tube, the curve of counts versus roentgens was flat to 10 percent from 120 to 300 KV. To include the very soft radiation under 60 KV he constructed a tube with a plexiglass wall, 1 mm thick, and operated it slightly below Geiger threshold in the region of limited proportionality. For energies in excess of 35 Kev, the current

(42) A. Trost, VDI - Zeitschrift 85,829 (1941)

delivered by this tube paralleled an "air wall" ionization chamber response within 10 percent. These results are illustrated in Fig. (18) reproduced from ref. (42).

#### Methods of Improving the Gamma Ray Efficiency

Any construction which increases the area of cathode surface per unit volume of the counter will increase the number of secondary electrons injected into the gas and thereby increase the efficiency. The exposed inner surface of a cylindrical cathode may be increased by a factor of  $\sqrt{2}$  over that of a smooth surface by cutting 45 degree threads on the inside, or by a factor of  $\frac{\pi}{2}$  by employing a closely wound helix of 16 or 20 gauge wire as the cathode. The greatest advantage was gained by the substitution of a wire mesh screen (43) for the solid wall cathode. The optimum mesh was found to be about 100 wires per inch and gave about a 50 percent improvement in efficiency over a smooth walled cathode of similar material. Part of this gain was attributed to the ability of the electric field to penetrate the apertures in the mesh and draw in electrons formed on the outside.

Bundling large numbers of smaller diameter tubes within the volume of a single large tube is another simple method of increasing efficiency, particularly when dealing with a collimated beam of radiation. Since perhaps 99 percent of the gamma ray beam is transmitted through the walls of the first cylinder, the second cylinder in the path of the rays has almost as much chance of producing a count as the first. Ten counter cylinders in line may therefore yield about nine times as many counts as a single counter placed in the path of a parallel bundle of rays. The counters shown in Fig. (19) were

(43) R. D. Evans and R. A. Mugele, R.S.I. - 7,441 (1936)



intended for use in this way. If, however, a number of smaller diameter cylinders are bundled in place of a single large tube of comparable over-all dimensions, the gain in efficiency for detection of an isotropic flux of radiation is not very great unless a very large number of tubes is used. The relative efficiencies of the bundle of tubes and the equivalent simple tube are given by the ratio of the sum of the diameters of the individual tubes to the diameter of <sup>the</sup> simple large tube. For a bundle of seven tubes, the ratio is  $7/3$ ; for 19 tubes the improvement in efficiency is only  $19/7$ .

Perhaps the most successful multi-element tubes designed to increase efficiency were described by Hare in a series of patents <sup>(44)</sup> filed in 1941-43. It is not necessary to retain the coaxial cylinder arrangement in order to obtain a Geiger counting plateau. Because of the concentration of the field near the wire, the plateau is relatively insensitive to the shape of the cathode. For example, a plane electrode may be substituted for the cathode cylinder (fig. 20A). This configuration may be expanded in one dimension as shown in (fig. 20B) and finally in two dimensions to form a multiplicity of both plates and wires, fig. (20C). The efficiency of such an assembly is approximately equal to the number of plates, even when as many as ten plates are used, and does not depend very much on orientation. Theoretically, the limit to the efficiency obtainable with such structures may approach 30-40 percent. Practical restrictions on the number of plates employed would be governed by the mechanical limitations on the closest spacings. Hare stated that spacings between plates of 2 mms. were successfully employed.

(44) U.S. Patent 2,397,073 to D.G.C. Hare (1946)  
U.S. Patent 2,397,071 to D.G.C. Hare (1946)

The extent to which the geometry of the counter may deviate from the simple coaxial cylinders and still retain full volume sensitivity, depends on the nature of the gas in the counter. With the more commonly used "100 percent efficient" mixtures such as argon-alcohol, a considerable asymmetry is tolerable. However, with halogen admixtures, halogenated hydrocarbons, and other electronegative gases, the loss of sensitivity in the weak field regions near the corners of a box counter of rectangular cross-section, for example, would leave most of that part of the counter volume insensitive to radiation. (45) Recently, Curran and Reid investigated the behavior of box shaped cathodes with various numbers of parallel wire anodes and determined the effects of asymmetries in anode positions relative to cathode walls and of anode spacings relative to each other.

Many other arrangements to increase the cathode surface have been suggested. The construction shown in Fig. (21A) consisting of a wire anode passed perpendicularly through a hole in a plate, will function as a Geiger counter. The sensitive volume of such a configuration extends out considerably farther than the radius of the hole in the neighborhood of the plate. Extending this arrangement as shown in Figs. (21B) and (22), leads to a structure of stacked disks perforated with holes that are aligned on common cylinder axes. The anode wires are strung axially through the holes. The entire assembly may be compared to a bundle of counters, the effective diameter of each counter being appreciably greater than the hole diameter because of the penetration of the fringing field between the plates. Again, Here cited the following figures:

(45) S.C. Curran and J. M. Reid, R.S.I. 19,67 (1948)

if the cathode plate was one inch in diameter, the hole  $5/16$  inch, and the plate spacing 0.1 inch, the same number of counts was obtained as with a conventional counter of  $1-3/8$ " diameter.

(46)

Du Mond described a form of multi-concellular counter in which the cathode structure was a stack of die cast lead alloy disks, each disk having a round hole at the center. As shown in Fig. (23), four anode wires spread out in the form of a spider between each pair of plates, from a common supporting rod extending through the holes in the centers of the disks. This type of tube was used to receive the converging beam of gamma rays from a bent crystal spectrometer designed to measure wavelengths up to 1 Mev. At 0.5 Mev the counter detected about 8 percent of the incident quanta.

Another multi-section counter recently described by Beyster and

(47)

Wiedenbeck was based upon a simple unit cell, any number of which could be stacked up to produce the desired increase in efficiency. Each cell resembled a flat cylindrical cheesebox, made of brass, 4 inches in diameter and  $1/2$  inch deep. The anode was a circular loop of 10 mil wire two inches in diameter, supported midway between the two faces of the box by glass insulated "feed throughs", waxed into the cylindrical wall of the box.

(46) J. W. M. Dumond, R. S. I. 18,626 (1947)

(47) J. R. Beyster and M. L. Wiedenbeck, R. S. I. 19,819 (1948)

## Beta Ray Counters

The specific ionization of beta rays is high enough so that any particle traversing the inter-electrode space of a Geiger counter is almost certain to trigger a discharge. The major problem in designing a beta ray counter is therefore one of providing a suitable window for the particles to penetrate from outside. Alternatively, a demountable counter tube may be used, which can be assembled with the sample inside the envelope of the tube, and then filled with the counting gas mixture.

The simplest type of beta ray counter closely resembles the ordinary gamma ray counter except that the cathode wall and envelope are thinned down to the extreme permitted by requirements of mechanical strength. Most familiar of this type is the thin glass wall tube, about 30 milligrams per  $\text{cm}^2$ , coated with a thin conductive layer of silver, copper, or colloidal graphite (fig. 24C). Because of the fragility of the thin blown glass portion, attempts have been made to achieve equivalent transparency in metal wall tubes. Two such tubes have been offered commercially, one fabricated of aluminum with a 0.005 inch wall, the other of chrome iron with 0.002 inch wall. The wall thickness of 30 mgs. per  $\text{cm}^2$  is generally considered to be the minimum compatible with requirements of mechanical strength and vacuum tightness, so that tubes of the thin wall type are unsuited for use with the softer beta ray emitters.

The thin walled counter has been used extensively to measure the artificially induced activities in foils which could be wrapped around the counter and measured after activation. Larger tubes of the same

form are well suited to filter paper measurements where again the paper is wrapped around the counter, exposing a relatively large surface to the cylindrical beta ray window. Fig. (24B) illustrates an adaptation of the thin walled tube for the measurement of beta activity in liquids. The thin walled thimble shaped end may be dipped directly into the liquid. In still another arrangement, the thin walled portion of the tube is surrounded by a jacket with provision for admitting the active liquid into one end of the jacket, circulating it about the thin walled portion, and finally passing it out the opposite end. (48)

The most popular type of beta ray counter is the end window tube intended for use with small flat disks of radioactive deposits. Mechanically, such a tube is identical with the x-ray counters of fig. (15) but the length of the cylinder is reduced to the minimum consistent with maintaining a flat plateau (fig. 27A). The dimensions are chosen with the intention of providing the maximum solid angle of collection and the minimum response to gamma rays and cosmic ray background. Reducing the length of the tube relative to its diameter creates end effects which increase the slope of the plateau and decrease its length. Most tubes compromise at a ratio of length to diameter between  $3/2$  and 2.

A more effective approach to the problem of increasing window area relative to cathode area is to construct a shallow counter bounded by two plane parallel cathode surfaces. One of these faces is the mica

(48) W. F. Bale, F. L. Haven, M. L. LeFevre, R. S. I. 10,193 (1939)

window conductively coated on the inner surface. The anode wire is mounted parallel to the plane of the window. An approach to such a construction was implicit in the early type of beta counter shown in fig. (25). The usual cathode cylinder was replaced by a half cylinder with its concave side open toward a thin window. In the tube illustrated, the window was an aluminum foil mounted on a supporting grid. The half cylinder was later succeeded by a multiplicity of half cylinders (fig. 26a) and finally by a flat plate, producing the shallow box form of counter (fig. 26b,c), one large face of which was the thin window. One or more anode wires were strung parallel to the cathode planes depending on the width of the box. Large counters of this type are widely used as air-proportional counters by laboratories of the A.E.C., with a thin nylon film coated with collodal graphite serving both as the window and one of the cathode plates. In principle, such an arrangement is well suited to beta ray counting when a vacuum tight window is provided and the counter is filled with a Geiger counting gas.

Another way of accomplishing the same result was suggested by Beyster and Niedenbeck in connection with the high efficiency gamma ray construction described above. Replacing one face of the shallow cylindrical box with a thin window (Fig. 27) produces a flat box counter with the same counting geometry as the ordinary end window counter but with a minimum of volume and cathode surface.

(49) R. Thompson and B. Liven, MDDC Report 99

(50) J. A. Simpson, R. S. I. 19,733 (1948)

inner surface of the mica slightly conductive.

One inch mica windows of  $1.5 \text{ mgs/cm}^2$  thickness are supplied in commercial tubes. Such windows are adequate for measurements of  $\text{S}^{35}$  (167 Kev) and  $\text{C}^{14}$  (145 Kev), but not thin enough for tritium,  $\text{H}^3$ , whose beta rays have maximum energy under 15 Kev. Extremely thin films of materials such as nitrocellulose, formvar, and evaporated silica, can transmit electrons with energies as low as one or two thousand electron volts. These films are sufficiently vacuum tight and strong enough when mounted on a fine supporting grid, that semi-permanent fillings can be made, which retain satisfactory counting characteristics for a day or longer.

In working with tritium, it is generally desirable to admit the radioactivity directly into the counter as part of the counting gas. (51)

The tritium can be converted to HTO water which may be introduced into the counting mixture as water vapor at a pressure of one or two millimeters Hg without seriously damaging the counting characteristics.

Alternatively, tritium gas may be electrolyzed from tritium water and used in the same manner as inactive hydrogen in a counter gas. If  $\text{C}^{14}$  (52) is carried in  $\text{CO}_2$  it may be used as the counting gas in combination with  $\text{CS}_2$  vapor and the aid of an electronic quenching circuit. About 2 cms Hg of  $\text{CS}_2$  is used with anywhere from 10 to 50 cms Hg of  $\text{CO}_2$ , providing thresholds from about 2000 to 5000 volts, depending on the tube dimensions.

(51) R. Cornog and W. F. Libby, Phys. Rev. 59, 1046 (1941)

(52) W. F. Libby, Anal. Chem. 19,2 (1947)

W. W. Miller, Science 105,123 (1947)

(53)

The screen wall counter shown in Fig. (28B) is illustrative of a demountable type in which the source is placed inside the envelope so as to eliminate the need for a window. Radioactive material to be measured is coated on the inside of the metal sample cylinder. This cylinder can be made of nickel so that it may be moved within the tube by means of an external magnet. The active volume of the counter is defined by the wire mesh cathode in the center of the tube. When the sample holder is in alignment with the screen cylinder as shown in the figure the counter presents a large solid angle to the source and accommodates a relatively large area of sample. Background count is determined with the sample cylinder drawn to one end of the tube, out of the sensitive region. Any suitable gas mixture may be used. It is recommended that the tube be operated with "drag in" voltage between the screen and the sample cylinder or outer wall so as to sweep out positive ions which drift outside the gauze. The disadvantage of this type of counting is, of course, the need for disassembling the tube every time a sample must be changed, a procedure which may consume about 20 minutes between sample measurements.

An apparatus which provides for quick sample changes and eliminates the inconvenience of disassembling and reassembling the counter tube, and evacuating before refilling, is that shown in Fig. (28A)

(54)

and known as a "gas-flow" counter. The sample is brought up close to

(53) W. F. Libby, D. D. Lee, Phys. Rev. 55,245 (1939)

(54) S. C. Brown, Phys. Rev. 59,954 (1941)



the mesh cathode through a side tube. Methane, helium, or a mixture of helium and a quenching gas stored in a high pressure tank, is admitted through the input sidearm. The incoming gas flushes the air out of the tube through a bubbling bottle. By maintaining a continuous flow of gas at atmospheric pressure it is unnecessary to have a perfectly vacuum tight system. The operating voltages need not exceed 2500 volts with methane and are much lower with helium mixtures.

The arrangement illustrated in Fig.(28A) is relatively crude compared to some more recent versions of gas flow counters which permit the use of larger samples and more efficient geometrical arrangements.

#### Size Limitations

There are many problems, particularly in medical physics and in nuclear physics, which call for the use of small size probes for gamma and beta ray detection. For example, in medical tracer work it may be desirable to determine the location of a radioisotope within the tissue of an animal or human "in vivo". The limitations on the extent to which the demensions of a Geiger counter may be scaled down have thus far been entirely mechanical. L. F. Curtis described <sup>(55)</sup> what is perhaps the smallest counter yet built. The glass envelope was coated with aquadag on the inner wall to form a cathode cylinder <sup>of</sup> only 0.8 mm I. D. and a length of 3 mm. The anode was a tungsten wire 0.005 mm in diameter. Curtis compared the size of the tube to a number 2 sewing needle as shown in Fig. (29). The tube was filled with the usual

(55) L. F. Curtis, Jour. of Res. NBS, 30,157 (1943)

amyl-acetate and argon mixture at 4 cms. Hg total pressure, and gave a background count of 20 per hour. Pulse size in such small tubes is comparable to or greater than is obtained in larger tubes. Because of the small volume of the tube it is natural to expect the life to be shorter than in larger tubes where the number of molecules dissociated per pulse constitute a smaller percentage of the total number originally present.

At the other extreme unusually large counters offer not constructional difficulties but they are inherently slow, have relatively high background rates, and a greater percentage of delayed and spurious counts. To avoid excessively high operating voltages, the anode diameter is ordinarily kept small while the cathode diameter is increased. The field throughout most of the counter volume is therefore relatively weak. As a result the electron collection time is longer and the positive ion sheath must cover most of the enlarged distance from wire to cylinder in a weak field with a consequent increase in the dead-time. In the enlarged, weak field part of the counter volume there is also a greater probability for negative ion formation, and delayed counts. Finally, the increased capacity slows up the recovery of the wire potential and broadens the pulse.

### Reduction of Dead Time

Stever's experiments demonstrated the existence of a natural dead-time of  $10^{-3}$  to  $10^{-4}$  second. The dead-time explained the choking of Geiger counters at rates of a few thousand counts per second, when used with low sensitivity amplifiers. (56) Trost found that the integrated current flowing thru a counter tube increased well beyond the "choking rate" as shown in fig. (30). The conclusion to be drawn from Trost's experiment was that pulses appeared within the dead-time, which were reduced in amplitude below the detection level of the amplifier. They were then not counted but contributed a reduced charge per pulse to the flow of current thru the tube. (57) Muehlhouse and Friedman using a sensitive wideband amplifier, measured counting rates as high as 100,000 per second in a Geiger tube whose resolving time at low rates appeared to be 10,000 per second. The dead-time decreased with counting rate above 10,000 per second in such a manner that a constant 40 percent of the counts were lost at any rate up to 100,000 counts per second.

(56) A. Trost, Zeits. f. Physik 117,257 (1941)

(57) C. O. Muehlhouse and H. Friedman, R. S. I. 17, 506 (1946)

(58)

Baldinger and Huber recently studied the behavior of counters at rates higher than the "Stever dead-time". At very high rates almost all pulses fell into the "recovery period" and the average pulse height became a small fraction of normal. These smaller pulses were followed by shorter dead-times. The dependence of dead-time on pulse height was linear down to pulses about one fifth normal amplitude, which was the range covered by the experiment. Increasing the amplifier sensitivity is therefore effective in raising the maximum counting rate but does not materially improve the resolution at low rates.

Attempts have been made to reduce the dead-time by reversing the collecting field immediately after information of the positive ion sheath so as to return the positive ions to the wire. The recovery time instead of being governed by the time required for the positive ions to cross the diameter of the counter, would then be reduced to the time required to cover the very small distance from the initial radius of the sheath to the wire. Simpson's original circuit for this purpose applied a high and adjustable negative pulse of a few microseconds duration to the wire. The pulse was derived from a fast one shot multivibrator, triggered by the amplified initial pulse of the Geiger discharge. Simpson

(58) E. Baldinger and P. Huber, *Helv. Phys. Acta* 20,238 (1947)

(59) J. A. Simpson, *Phys. Rev.* 66, 39 (1944)

estimated that the improvement in speed of ion collection obtained this way could reduce the dead-time by almost a factor of ten.

Other reversing circuits have since been described by (60) and by Smith (61) but they attributed most of the dead-time reductions which they obtained to limitation of the discharge spread rather than to positive ion collection. Before the discharge could propagate the full length of the tube, the wire potential dropped below threshold, bringing the discharge to a stop and leaving the remaining length of the counter still sensitive. Since the rate of spread of the discharge is about 10 centimeters per microsecond, this effect is most readily observed in a long counter. Extremely fast circuitry would be required to limit the discharge spread appreciably in a short counter. Smith estimated that ion collection alone reduced the dead-time by only a factor of two and cautioned against the possibility of interpreting spurious pulses which arise from secondary emission at the wire during the positive ion collection period, as evidence of dead-time reduction.

An effective way to reduce the dead-time is to limit the discharge spread along the wire by the use of glass beads. If, for example, the counter wire were divided into two equal lengths by a bead at the center, it would behave as two separate counters connected in parallel. The effective dead-

(60) A. L. Hodson, Jour. Sci. Inst. 25, 11 (1948)

(61) P. B. Smith, R. S. I. 19, 453 (1948)

time of the combination would then be half the dead-time of either section alone. Because the positive ion sheath is only half as long, normal pulse amplitude must of course be only half that of the same counter minus the bead on the wire.

Substituting a bundle of small counters for the equivalent volume of a single large counter, will increase the resolution by more than simply the number of counters in the bundle, since each counter of the bundle will itself have a shorter dead-time than the single large counter. Multi-element structures of the types illustrated in Figs. (19-23) show similar gains in resolving power. The parallel plate and wire structure is particularly effective because the small spacing of individual plates in itself produces a short dead-time per element. In open structures such as the tube of Fig. (22), only a few percent of the discharges can spread from one wire to another because of the strong absorption of ultraviolet light in fillings of rare gases in combination with polyatomic quenching admixtures. The effect on resolution is almost equivalent therefore to operation of independent counters in parallel. If such a tube is filled with simple gases or the rare gases with halogen admixtures, the discharges spread throughout the entire structure and the effect of limiting each discharge to a single wire is lost.

## Background Reduction

When measuring weak activities, the ultimate sensitivity of the counting method is controlled by the background count against which the sample activity must be distinguished. This background consists of cosmic radiation, gamma rays from natural radioactivity in the surroundings, and, in many laboratories, stray radiation from nearby accelerators. A rough figure for the cosmic radiation is about 1.5 cosmic rays per minute per square centimeter of horizontal surface at sea level. The larger the background, the more difficult it becomes to detect a small increase in counting rate. For example, if the background is equal to the counting rate being measured, then six times as many counts are needed to achieve a given statistical accuracy compared to the number required in the absence of background. If the ratio of sample count to background is as low as one tenth, then 121 times as many counts are required as in the absence of background. The advantage to be gained by any technique which reduces background is obvious.

In discussing the construction of Geiger counters for beta ray measurements, consideration was given to designs in which the ratio of sensitive volume to window area was minimized, thereby improving the ratio of beta count to background. It is customary to surround a counter and the sample to be measured by a lead shield which effectively eliminates the

gamma ray background, but does not stop the penetrating cosmic ray particles. However, because the efficiency of cosmic ray particle detection with Geiger counters is close to 100 percent, it is a simple matter to screen out the counts due to penetrating cosmic ray particles by anti-coincidence circuitry.

Fig. (31) illustrates an arrangement of high geometry for beta ray detection combined with an anti-coincidence shield. Two end window beta ray counters are mounted face to face with a sufficient gap between them to accomodate a flat sample. The sample material may be supported on a thin aluminum foil or plastic film which is capable of transmitting almost all the beta rays emitted by the radioactive atoms in the sample. With a small source, this arrangement collects nearly every particle emitted over the entire solid angle or presents what is ordinarily referred to as a  $4\pi$  geometry. The circuitry is so arranged that single random firings of the two counters are transmitted to the scaling circuit, but coincident pulses, excited by the passage of the same cosmic ray particle through both tubes are rejected. The cosmic ray shield is completed by slipping the anti-coincidence guard counter down around the two beta counters. The guard counter as illustrated is equivalent to a cylindrical ring of counters connected in parallel. Any coincidence between this shield counter and either of the two beta counters is rejected by the electronic circuit. The net result achieved by this



arrangement for rejecting coincidence counts is to reduce the background, after shielding in lead, by still another factor of five, without loss of beta ray counts. Fig. (31) illustrates a system employing two conventional end window counters. It is immediately apparent that shallow counters of the type shown in Fig. (26,27) are still better suited to anti-coincidence counting. If the depth of each Geiger counter is much less than its window diameter, then it is possible to dispense with the outer cylindrical shield and rely entirely on rejection of coincidence between the two beta ray counters.

Gamma ray counters of the multiple element types illustrated in figs. (19-23) are well suited to the application of anti-coincidence counting. Fig. (32) is a photograph showing the variety of pulse amplitudes observed on an oscilloscope with the counter of fig. (22) exposed to gamma rays. Since the anodes and cathodes are connected in parallel, coincidence pulses on more than one wire appear with double, triple, quadruple, etc. amplitudes depending on whether two, three, four, etc. wires are fired by the passage of a single particle. The great majority of the pulses are single counts typical of gamma rays. Occasionally the Compton electron ejected by a gamma ray traverses the fields of two wires and a few percent of the discharges spread from one wire to another leading to double amplitude counts. Triple amplitude pulses from gamma rays are very infrequent. On the other hand, all wires whose sensitive regions are cut by the trajectory of a

cosmic ray particle, fire in coincidence. The largest pulses are therefore produced by a cosmic ray particle penetrating the tube along a plane through its axis. If the cosmic ray penetrates fewer elements of the tube, pulses of lesser amplitude result. By selecting the proper pulse amplitude discrimination level, it is possible to reject pulses above a given level so as to eliminate almost all background from penetrating cosmic rays.

#### Directional Counters

The production of a preferred directional sensitivity in a gamma ray counter without the benefit of external shielding by means of lead or other high density absorbers, is rather difficult to achieve in any high degree. Since the efficiency of counting depends on the material of the cathode wall, its thickness, and distribution in the path of the beam, it is possible to construct a tube so as to present a higher counting efficiency to a source in one direction than in others. Also, since gamma rays are detected mainly by virtue of the ejected Compton electrons which have a predominantly forward distribution, a tube that is responsive to electrons moving in a particular direction, should therefore be directional in response to the primary gamma rays.

(62)

Rajewsky described a bimetallic cathode for a gamma ray counter consisting of two hemicyclinders of lead and aluminum. Because of the different efficiencies of the two

(62) B. Rajewsky, Zeits. f. Physik 120, 627 (1943)

metals, the counting rate for rays entering lead and leaving aluminum was greater than for rays travelling in the reverse direction. Craggs and his coworkers (63) recently determined the contrast in sensitivity obtainable by such tubes with the aid of a parallel plate and wire form of counter. Diametrically opposed windows were cut in the glass envelope of the tube at positions orthogonal to the planes of the plates. These windows were covered with aluminum foil .002" thick. The response of this counter to a collimated beam of gamma rays was 32 percent lower when the beam passed through the windows than when it was directed perpendicularly to the surfaces of the plates. This experiment indicated the extreme of contrast obtainable in a bimetallic form of directional counter.

The experiments of Stever have showed that it was possible to localize the discharge in a Geiger counter by placing glass beads on the anode wire. If the beads were opaque to ultraviolet light the spreading of the discharge by photoelectric effect in the gas was blocked at the bead. Stever suggested the use of the beaded wire counter as a directional detector of energetic particles. For example, if the wire were partitioned into three sections by glass beads, a particle traversing the tube in a direction normal to the axis, would fire only one section, whereas a particle traversing the counter parallel to the axis would fire all three sections. Since the pulse amplitude developed by the counter is proportional to the length of the discharge along the wire, a circuit which

(63) J. D. Craggs, P. W. Bosley, A. A. Jaffe, Jor. Sce. Inst. 25,67 (1948)

discriminates against smaller pulses arising from the firing of one or two sections rather than all three will register only those counts arising from the triggering of all three sections by a primary particle travelling essentially parallel to the axis of the counter.

Since high energy gamma rays produce a distribution of recoil electrons with a maximum in the forward direction, a Stever type of beaded wire counter should have directional properties for gamma ray detection. However, because of the angular distribution of recoil electrons, the directionality of response is not very pronounced and the counting rate is corresponding low.

The most satisfactory arrangements for obtaining directional sensitivity with gamma counters are those which simply employ shielding with lead or other high density absorbers. When the gamma rays are emitted from a point source, it is advantageous to use two counters separated by a lead barrier and coupled to a differential counting rate meter.

#### Photon Counters

The photon counter combines the principle of the photocell with the amplification mechanism of the G-M counter. Rajewsky (64) and Locher (65) described the behavior of such tubes in 1931. Much of the work since then has been confined

(64) B. Rajewsky, Phys. Zeits. 32, 121 (1931)

(65) G. L. Locher, Phys. Rev. 43, 211 (1933)

to ultraviolet counters operating in the region below 3000A, although Locher achieved considerable success in the preparation of blue sensitive (threshold 4000 A. U.) tubes. So little effort appears to have been expended on the production of photon counters with long wavelength sensitivities that it is difficult to evaluate their possibilities. Of all detectors, the photon counter has inherently the maximum sensitivity for measuring the photo-current, i.e. it counts every photo-electron. To date, however, it has not been possible to duplicate in gas filled tubes the quantum yields obtained with photo surfaces in vacuum in the spectral range from 3000 A to 5000 A. Surfaces that are highly photosensitive in vacuo when exposed to visible light are invariably poisoned and desensitized by contact with the gas in a counter. At shorter wavelengths in the ultraviolet, however, quantum efficiencies between  $10^{-4}$  and  $10^{-3}$  counts/quantum are commonly obtained in photon counters. (66) These yields are comparable to those observed for most photo-surfaces in vacuum in that region of the spectrum.

Locher described many surface coatings and treatments which produced enhanced quantum yields in photon counters operating in the blue and ultraviolet portions of the spectrum. Since Locher's experiments very little has been published on photon counters. (67) More recently, Scherb described unusual spectral sensitivities obtained by glow discharging

(66) O. S. Luffendack and W. E. Morriss, J.O.S.A. 32, 8(1942)

(67) M. V. Scherb, Phys. Rev. 73, 86(1948)

an argon butane filled copper cathode counter at liquid air temperature. Fig. (33) illustrates the results of this treatment which produced a peak at about 3000A with a quantum yield about 15 times as great as that of the untreated copper surface between 2000 and 25000A. It seems reasonable to expect many similar improvements to develop out of research on photon counters if an effort were made to continue such investigations. There are interesting possibilities for the application of such tubes to spectroscopic instruments and in connection with scintillation counting.

### Conclusion

The writer has limited the contents of this paper to a discussion of Geiger counter tubes for the detection of cosmic rays, x-ray, gamma rays, beta particles, and ultraviolet light. Neutrons, protons, and alpha particles are ordinarily detected by means of proportional counters and pulse ionization chambers which do not fall within the scope of this paper.

Footnote: The references cited here represent only a small portion of the published literature on Geiger counter tubes.

- Fig. 1. Fundamental Geiger tube circuit.
- Fig. 2. Approach to uniform pulse amplitudes near Geiger counting threshold. Counter tube dimensions, (10, 1.0, 0.0125) cms. Argon-ammonia filling.
- Fig. 3. Gas amplification versus voltage in coaxial cylinder type of ionization tube.
- Fig. 4. Variation of threshold voltage with composition and pressure of self quenching gas mixture. After Trost (Ref. 2).
- Fig. 5. Dependence of pulse amplitude on counter tube dimensions and overvoltage. Tube dimensions are indicated as cathode radius (mm), wire radius (thousandths of a cm). After Trost (Ref. 2)
- Fig. 6. Effect of series resistance on pulse shape. The counter tube had the dimensions (10, 1.0, 0.0125) cm. and a capacity of a few micro-microfarads. The series resistance R was varied to alter the RC constant of the fundamental circuit, fig. (1). Strips A to H were taken with an argon- $\text{CH}_2\text{Br}_2$  mixture in the counter. The time markers on each trace are identified alongside each strip. Traces B, D, and F were photographed with a recurrent sweep. All the others are triggered sweep patterns. Strips I and J illustrate the effect of overvoltage on the rise time of the pulse in a neon-argon-chlorine mixture with a threshold of 550 volts. Trace I was taken at an overvoltage of 50 volts, trace J at 300 volts. All photographs were made with a Dumont Type 248 oscilloscope.



Fig. 7. (A) Deadtime pattern photographed on triggered sweep.  
 (B) Schematic representation of deadtime pattern indicating deadtime  $t_d$ , at foot of envelope of pulses triggered during recovery interval from  $t_d$  to  $t_r$ .  
 (C) Variation of electric field at the anode surface during period of ion sheath transport from anode to cathode.

Fig. 8. Plateau curves for mixtures of neon-hydrogen and argon-hydrogen obtained with a Neher-Harper electronic quenching circuit.

Fig. 9. Effects of impurity gases on the breakdown characteristics of the rare gases. (After Penning, ref. 23). Fig. 9A shows the effect of different concentrations of iodine and mercury in argon and neon on the breakdown voltage of the discharge between parallel plates about 1 cm. apart. The argon pressure was 15 mm, neon pressure 21 mm, and the admixture concentration was controlled by its vapor pressure at different temperatures. Fig. 9B is a semi-logarithmic plot of the Ne-Hg data in percentage of admixture versus decrease in  $V_B$ . A similar curve is shown for neon with small percentages of argon admixture. The data of Fig. 9C were obtained by starting with 0.06 percent argon in 10.1 mm of neon, which gave a  $V_B$  of 159 volts, and then diluting the mixture with neon up to a maximum pressure of 112 mm, which raised  $V_B$  to only 185 volts.

Fig. 10. Appearance of multiple pulses with insufficient admixture of quenching vapor. All traces were photographed at an overvoltage of 100 volts. Initial filling was argon, 20 cms Hg, plus  $\text{CH}_2\text{Br}_2$ , 0.5 mm Hg., which showed single pulses, trace A. Successive dilutions of the  $\text{CH}_2\text{Br}_2$  were made by pumping the mixture to 10 cms Hg. and restoring 10 cms. of pure argon. Traces B to F illustrate the appearance of increasing numbers of spurious counts with removal of the quenching agent.

Fig. 11. Development of spurious pulses at high overvoltages. The filling was 20 cms Hg. of argon plus 10 mm Hg. of  $\text{CH}_2\text{Br}_2$ . Threshold was 1500 volts. At overvoltages in excess of 300 volts, multiple pulses appear with uniform spacings characteristic of secondary emission due to positive ion bombardment of cathode. Higher overvoltages increase the average length of the trains of pulses and their frequency of occurrence. Marker pulses are 2500 microseconds apart.

Fig. 12. Effect of gas mixture on spacings between multiple pulses. Traces A, B, and C were made with 75, 35, and 15 cms Hg of argon respectively and a constant admixture of 10 mm Hg of  $\text{CH}_2\text{Br}_2$ . As the pressure of the argon was reduced the mobility of the positive ions increased and the intervals between pulses became shorter. Trace D illustrates the greater mobility in helium as

compared to argon. All markers are spaced 2500 micro-seconds apart but the right hand portion of Trace D is expanded. Traces E and F show the opposite trend toward decreasing mobility in a heavier gas such as Xe.

Fig. 13. Variation of counting rate with radial distance from anode. The counter tube was scanned with a fine pencil of x-rays traveling parallel to the anode. (After Friedman and Birks, Ref. 39).

Fig. 14. Absorption of soft x-rays in ten centimeters of the rare gases at various pressures. A-krypton, 76 cm Hg; B-krypton, 40 cm Hg; C-krypton, 20 cm Hg; D-xenon 20 cm Hg; E-argon, 76 cm Hg; F-argon, 40 cm Hg; G-argon, 20 cm Hg; A'-continuation of A; B'-continuation of B. (From Ref. 39).

Fig. 15. End window constructions for soft x-ray counters.

Fig. 16. Ratio of secondary electrons to primary gamma rays (2 Mev) emerging from aluminum absorbers of different thicknesses.

Fig. 17. Efficiencies of gamma ray counters with brass or lead cathodes in the spectral range from 0.1 to 2.6 Mev. Curves 1a, 1b, and 1c are the theoretical contributions from photoelectric effect, Compton scattering and pair production in brass. Curve 2 for brass and that for lead are experimental. (After H. Brodt, et al, ref. 41).

Fig. 18. Ratio of ionization chamber current to output of a Geiger counter (A) unfiltered, (B) filtered, and a proportional

counter (C) made of plexiglass. (After Trost, ref. 42).

- Fig. 19. Multiple counter tubes in parallel combinations.
- Fig. 20. Multiple plate and wire construction of gamma ray counter.
- Fig. 21. Perforated disk type of construction for high sensitivity gamma ray counter.
- Fig. 22. Photograph of multiple disk counter.
- Fig. 23. Multi-cell gamma ray counter. (After DuMond Ref.46)
- Fig. 24. (A) End window beta ray counter.  
(B) Thin walled dipping counter  
(C) Thin walled beta counter.
- Fig. 25. Beta ray counter with hemi-cylindrical cathode.
- Fig. 26. Development of flat box form of beta counter from hemi-cylindrical cathode structure.
- Fig. 27. Low background beta ray counter with loop form of anode.
- Fig. 28. (A) "Gas flow" beta ray counter for internal samples.  
(B) Demountable beta ray counter for internal samples.
- Fig. 29. Miniature Geiger Counter. (After Curtiss, ref. 55).
- Fig. 30. Counting losses due to deadtime. The amplifier responded to pulses as small as half normal amplitude.  
(After Trost, Ref. 56).
- Fig. 31. Schematic arrangement for background reduction.

Fig. 32. Variety of pulse amplitudes obtained from tube of  
fig. 22.

Fig. 33. Ultraviolet sensitivity of activated photon counter  
tube. (After Scherb, ref. 67).

# FUNDAMENTAL GEIGER COUNTER CIRCUIT

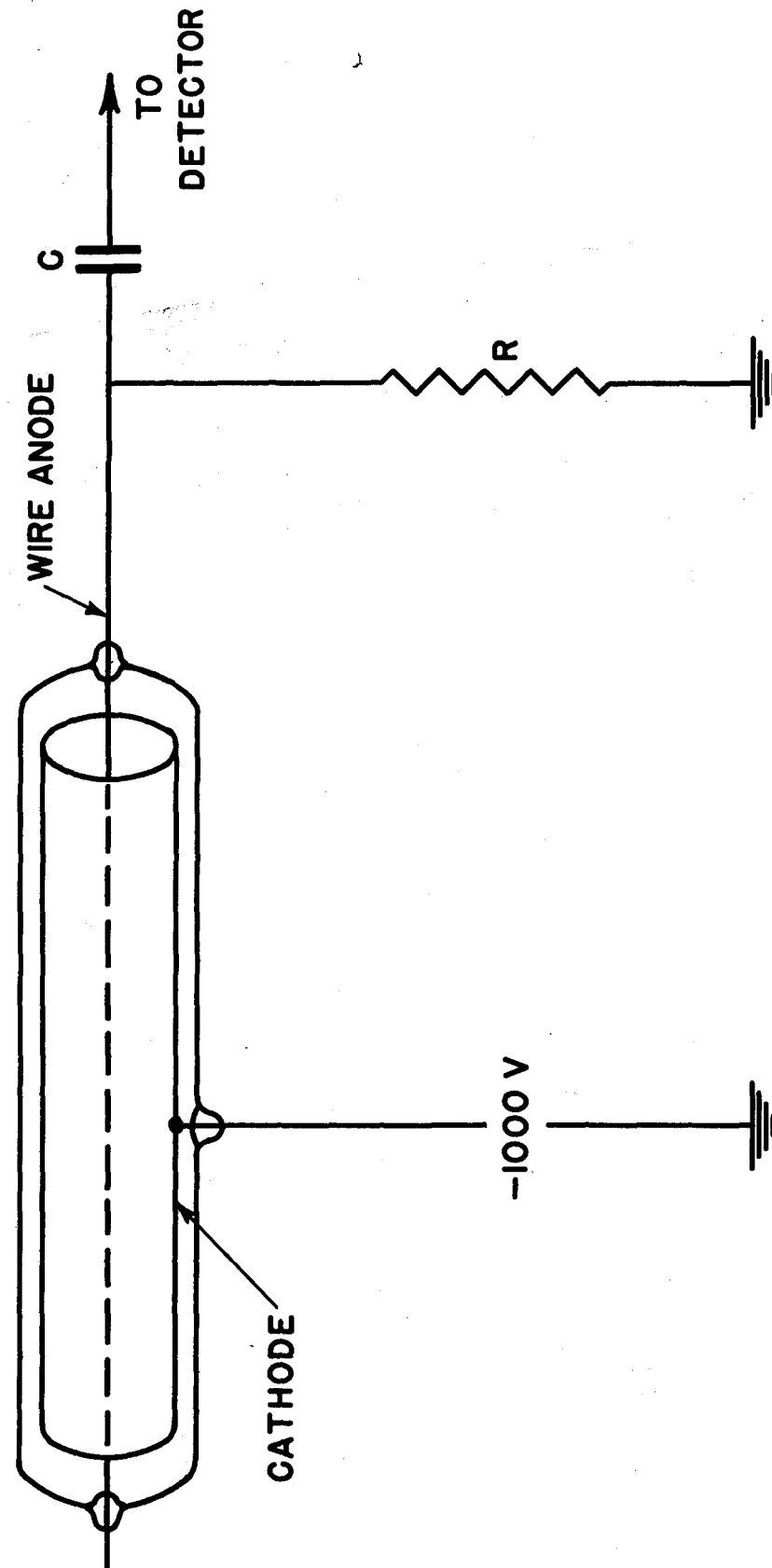


FIG. 1

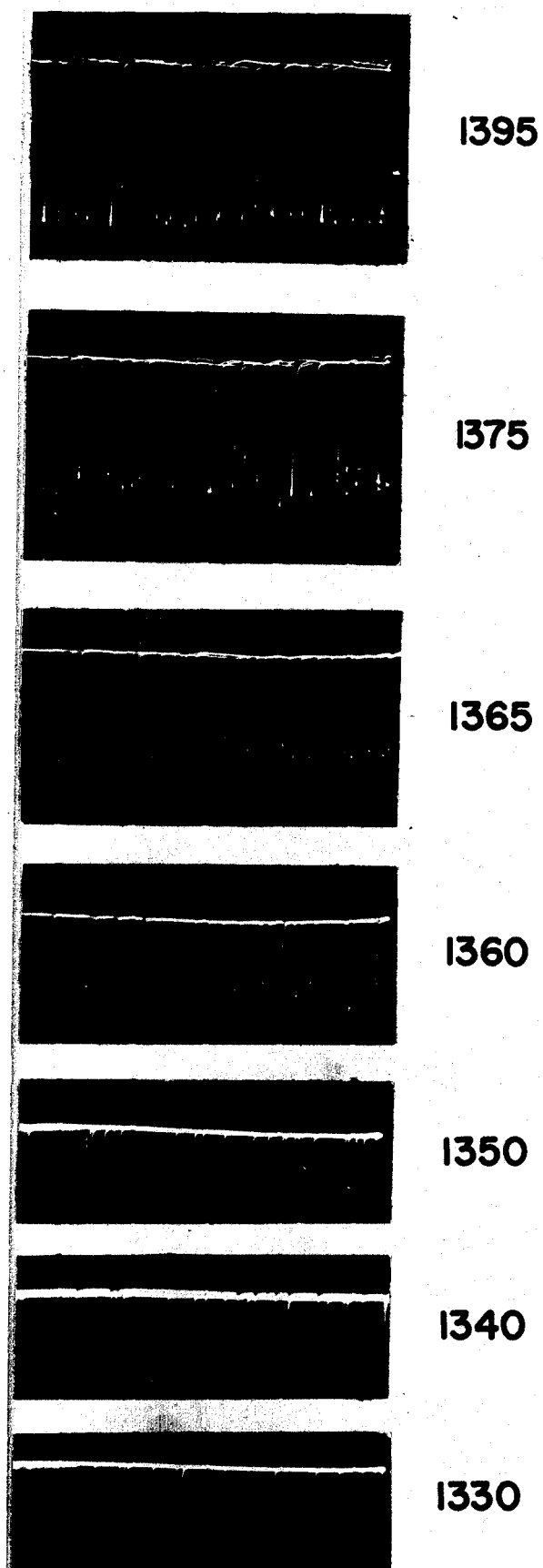


FIG. 2

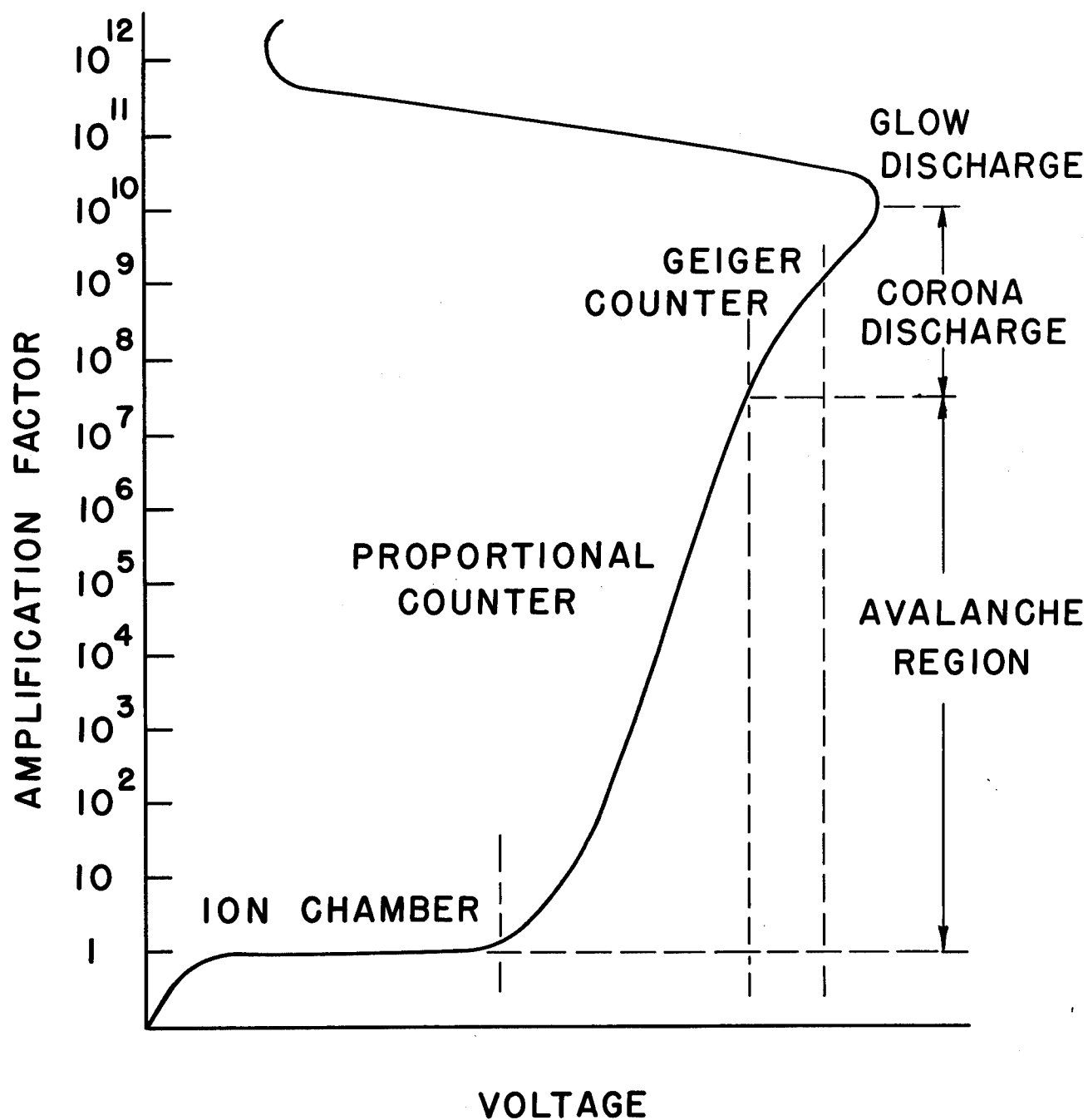


FIG. 3



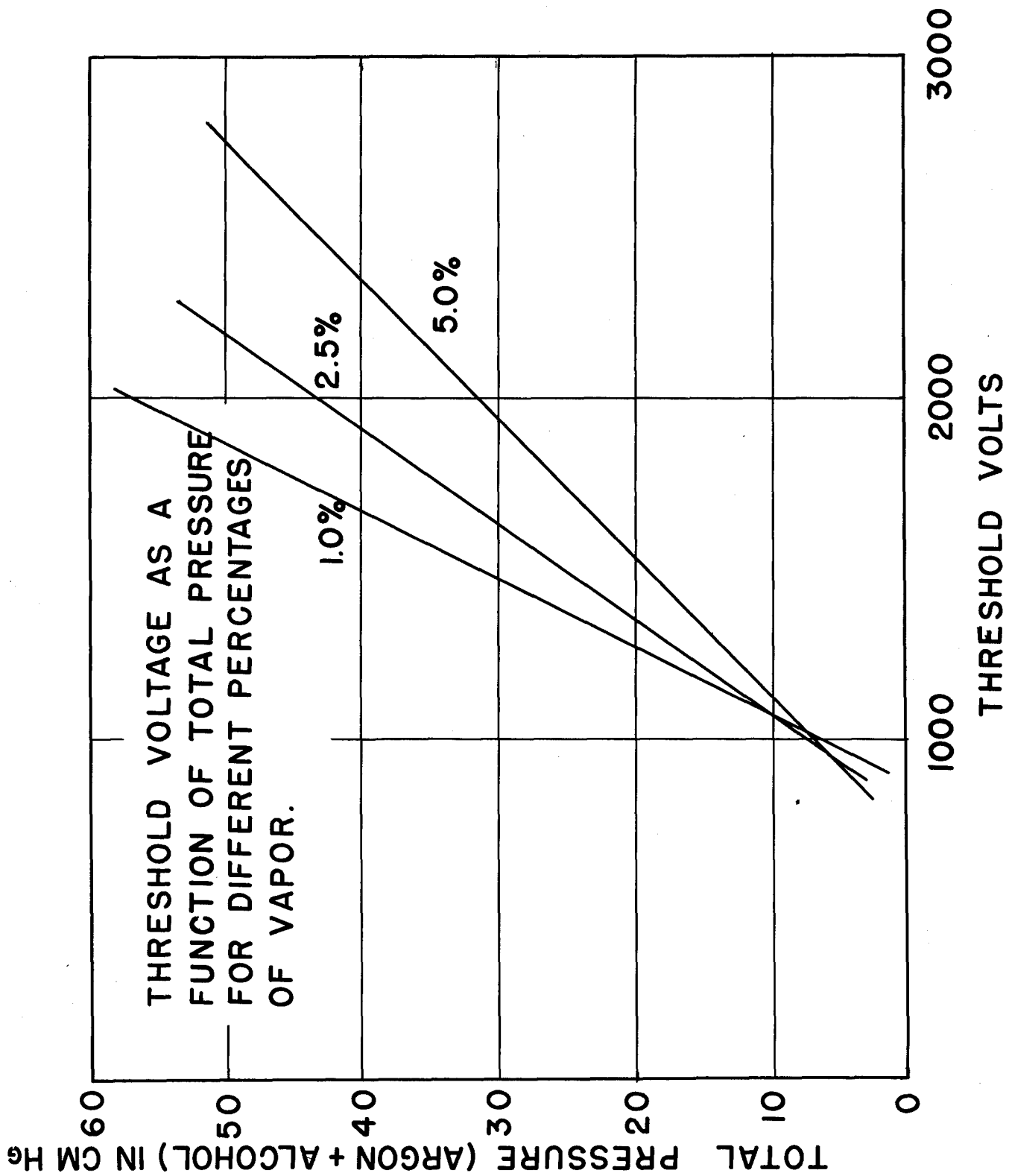


FIG. 4

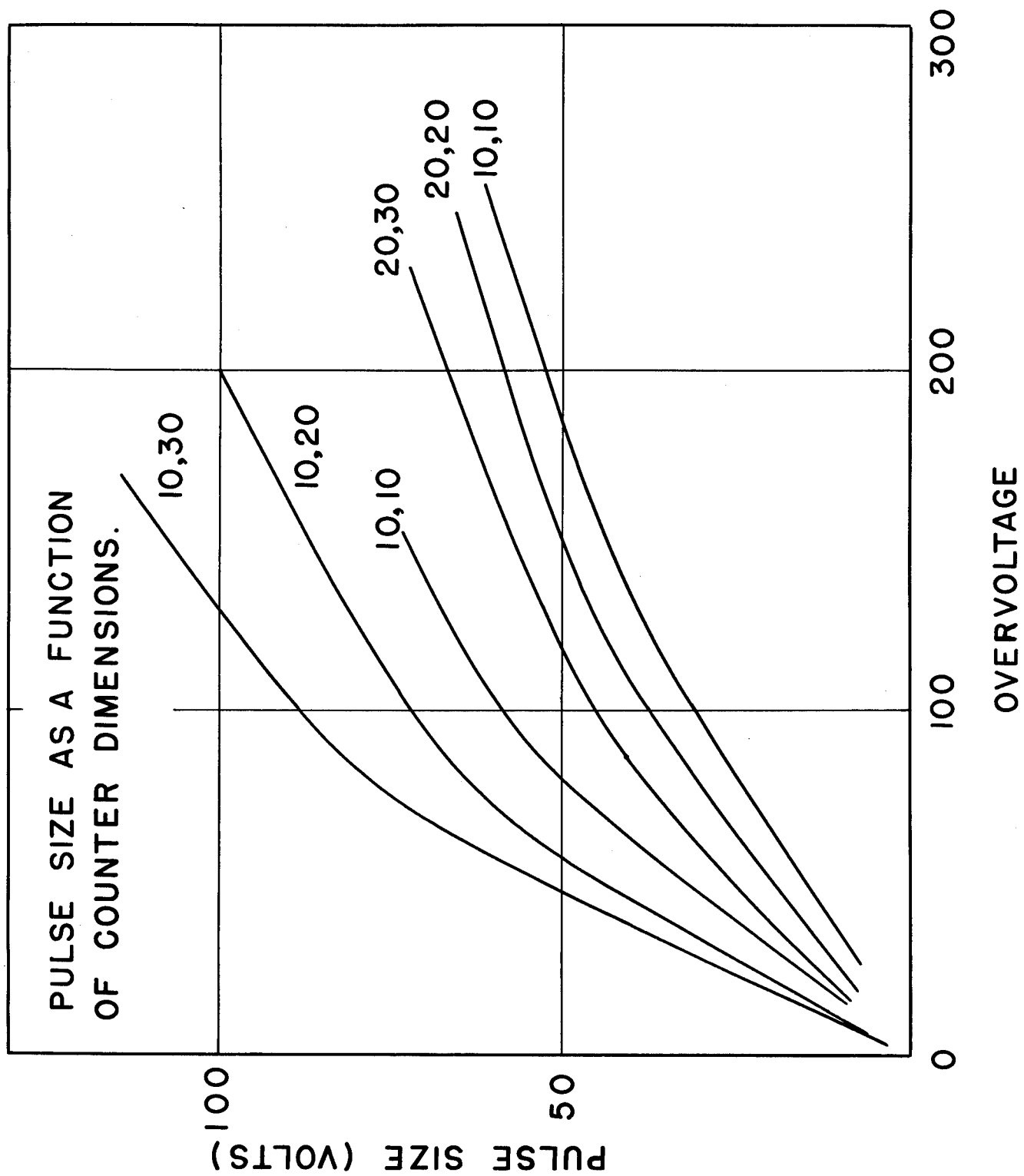


FIG. 5

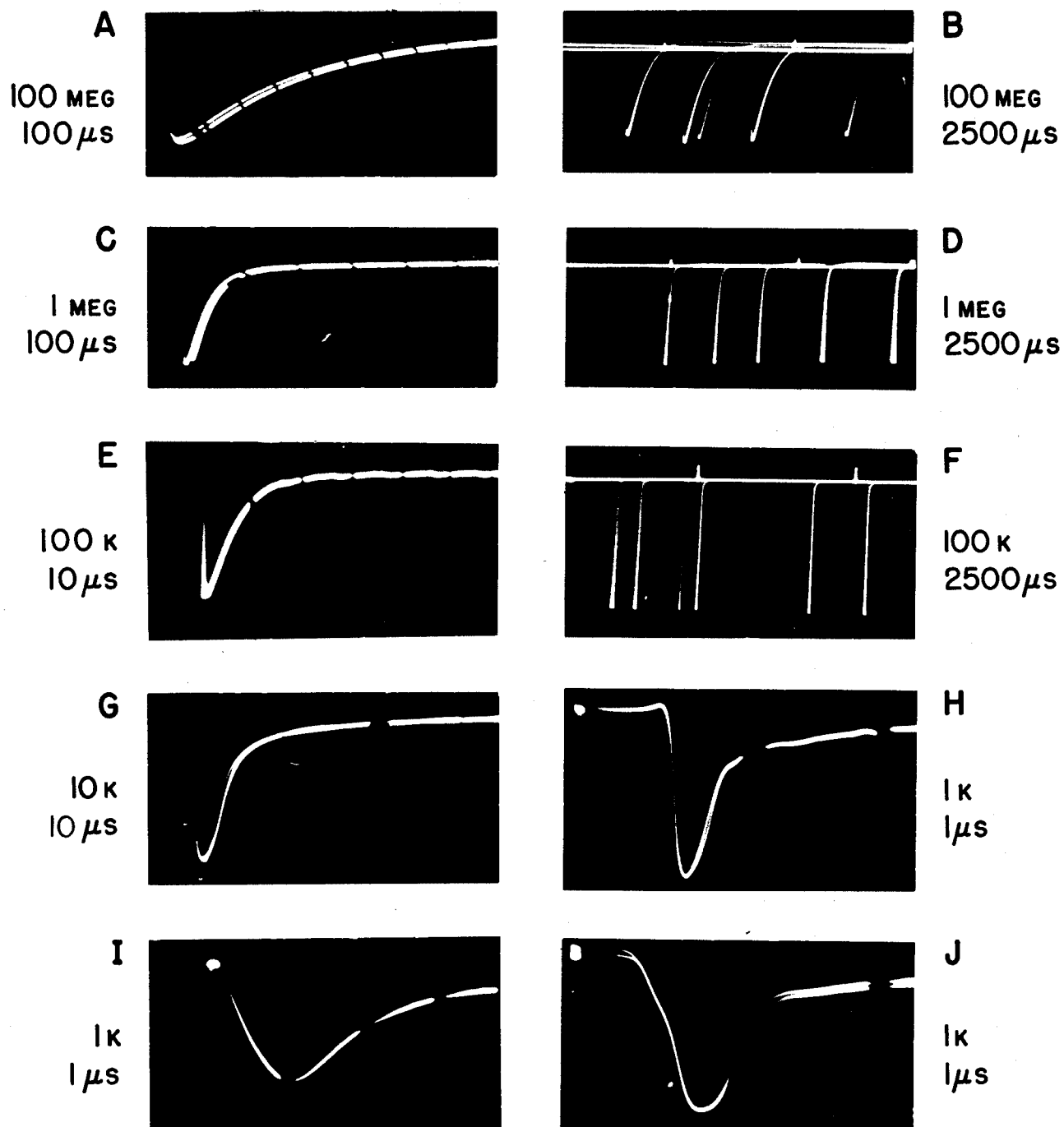
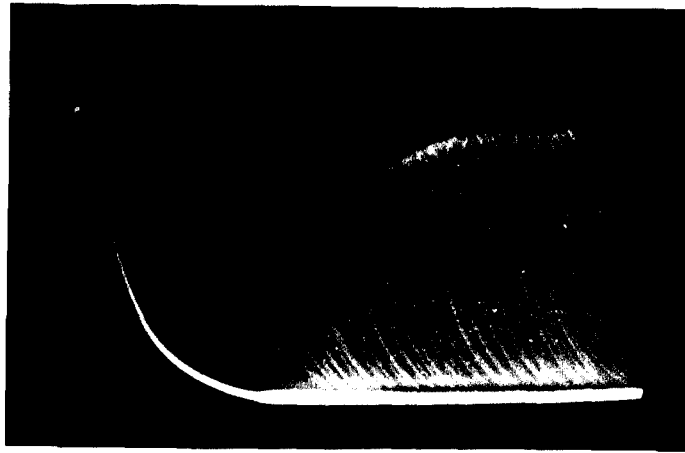
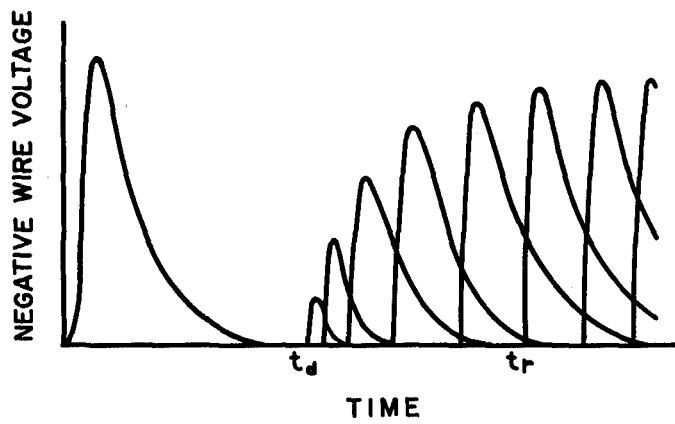


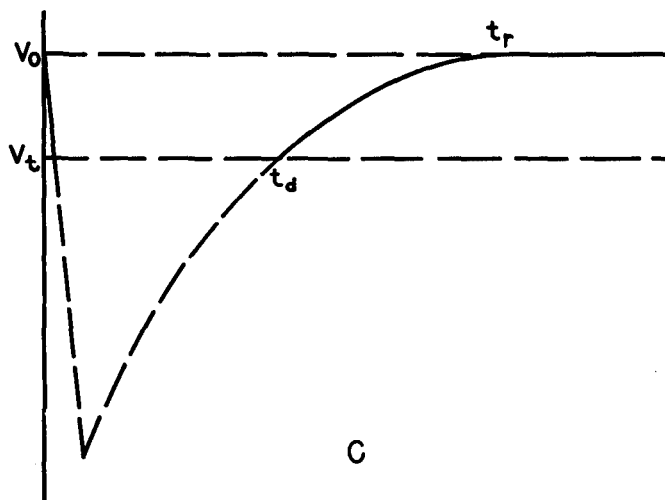
FIG. 6



A



B



C

FIG. 7

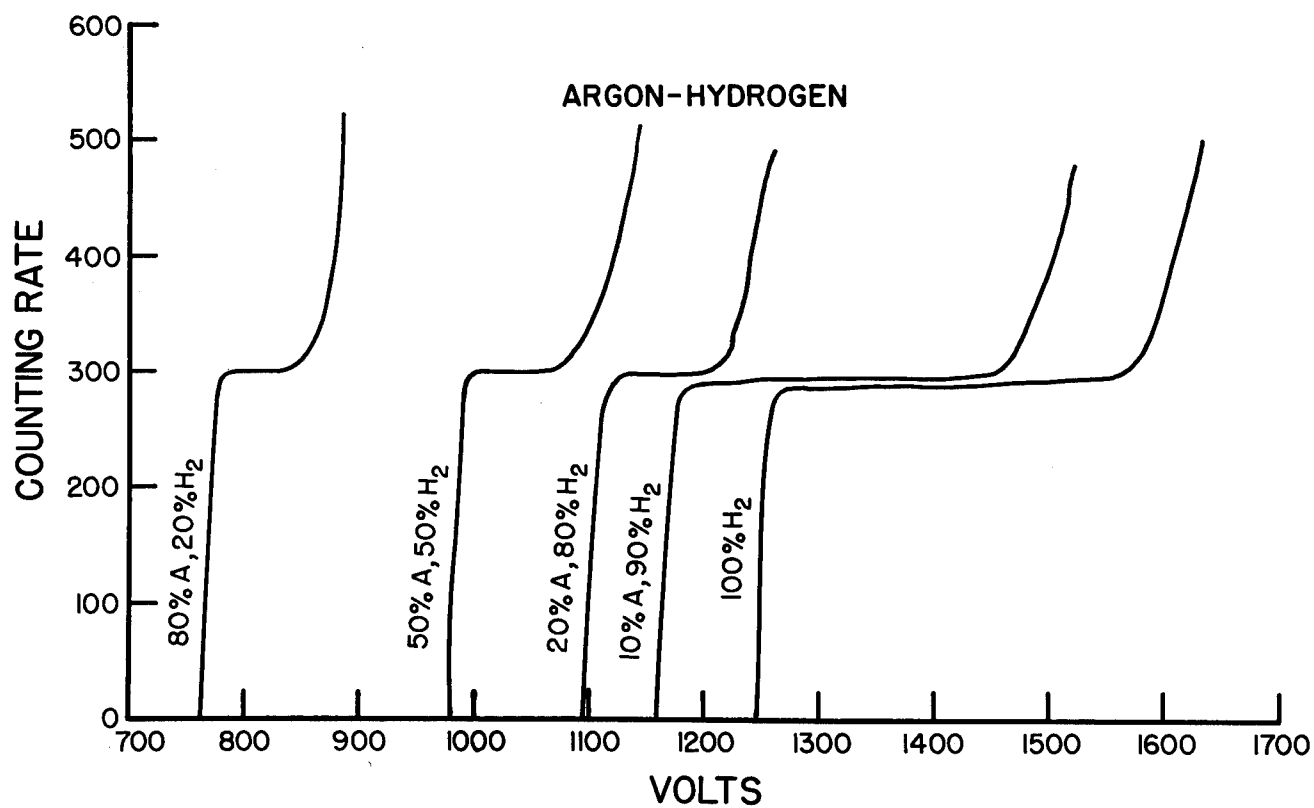
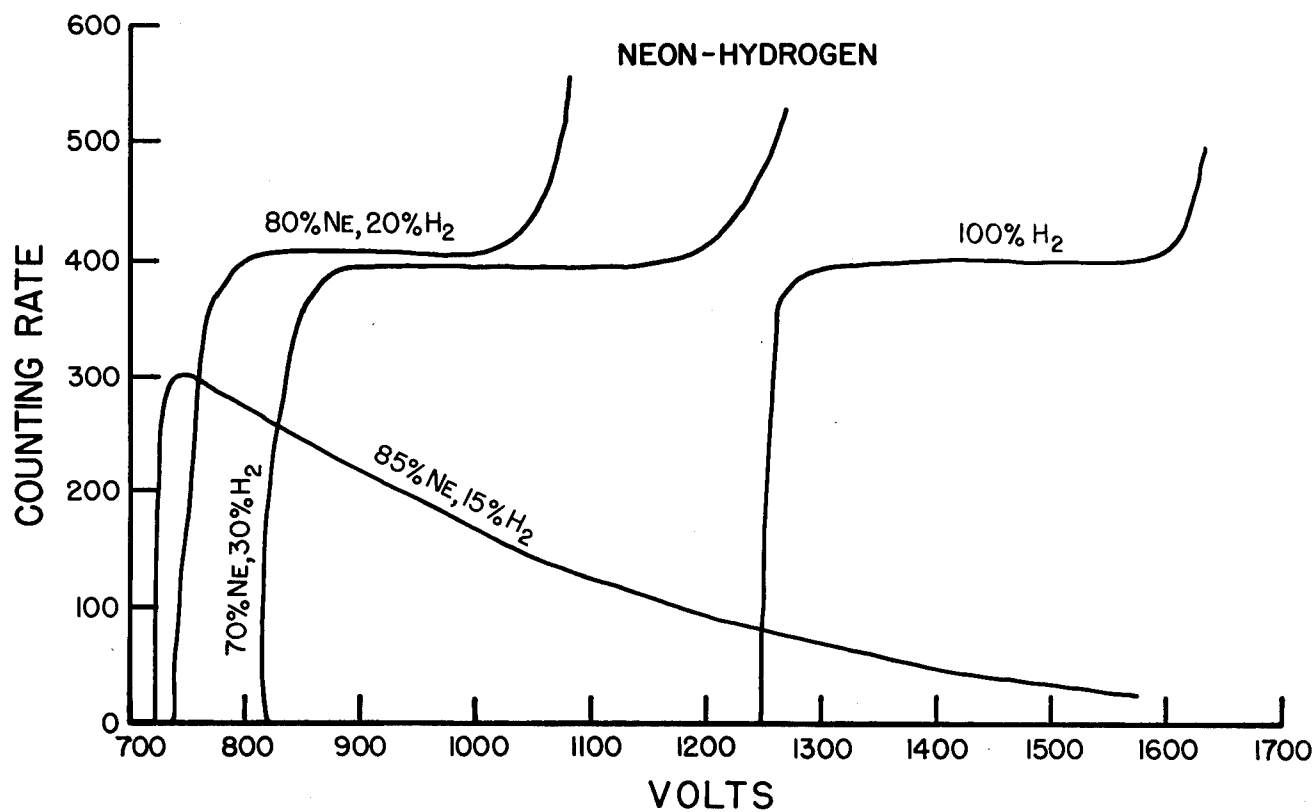


FIG. 8

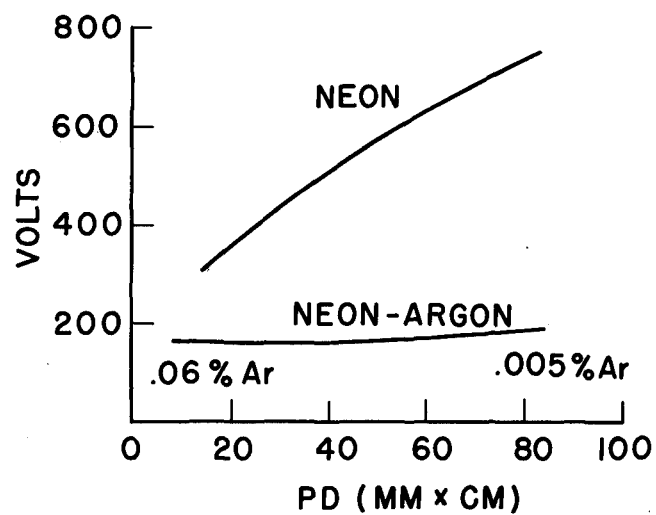
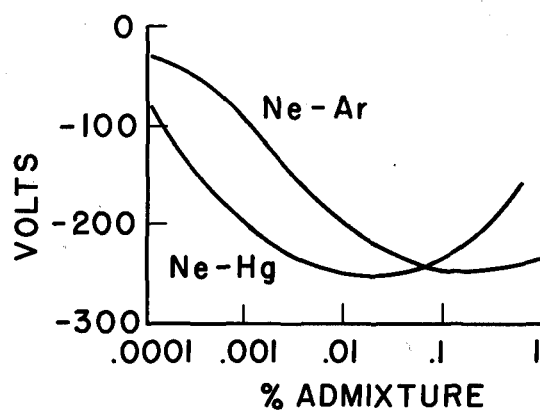
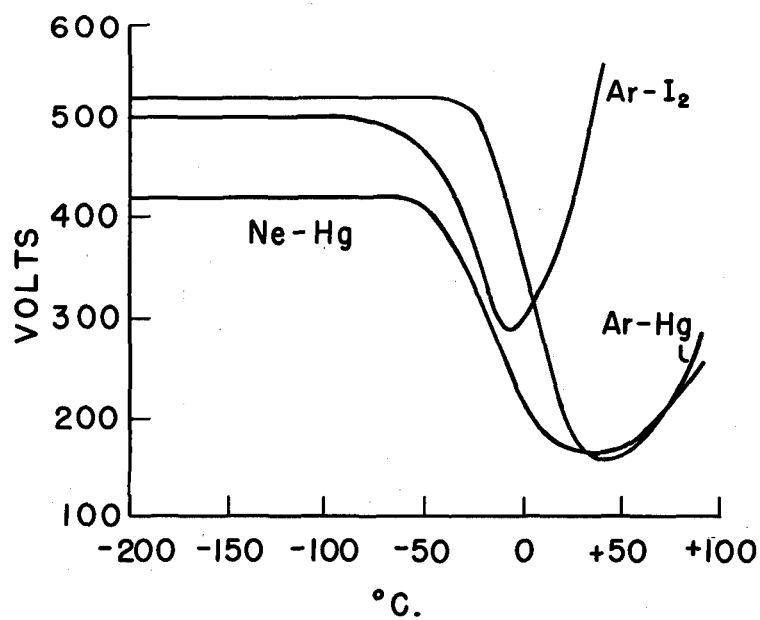
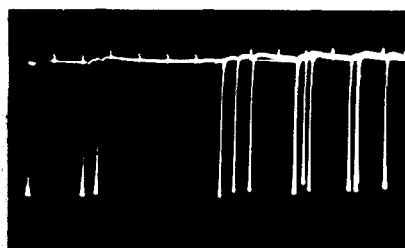
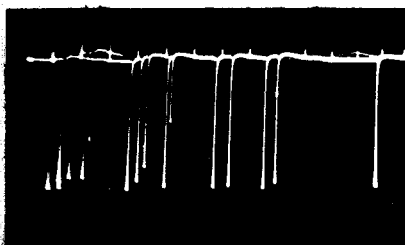


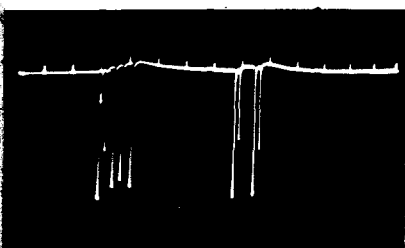
FIG. 9



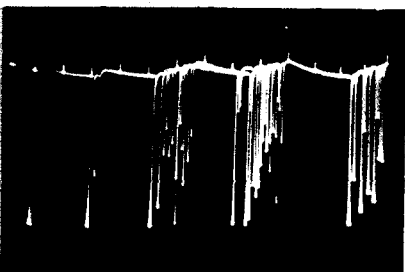
A



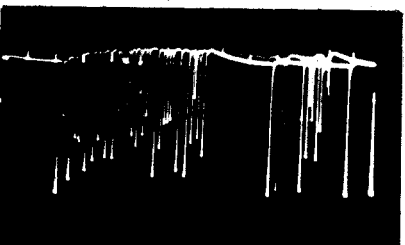
B



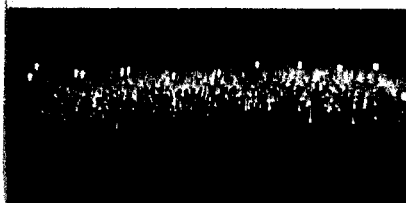
C



D

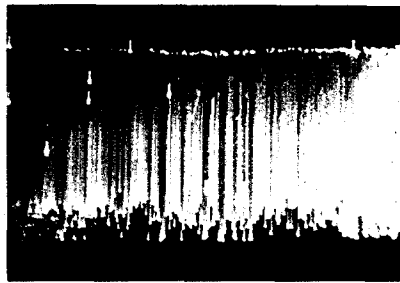


E

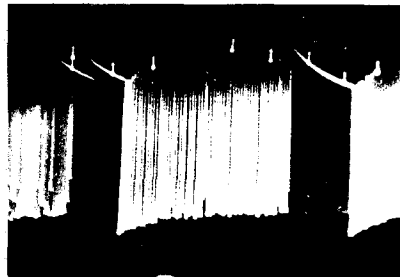


F

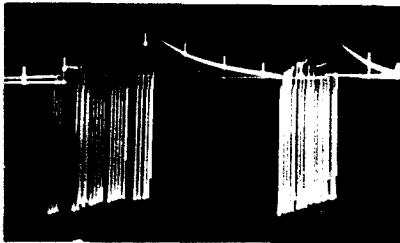
FIG. 10



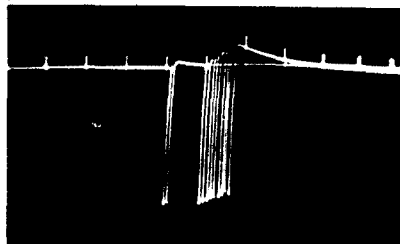
2100



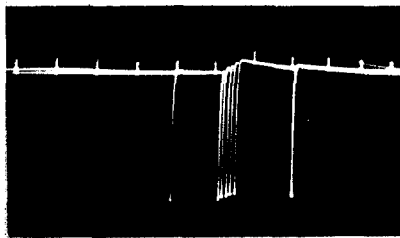
2000



1950



1900



1850

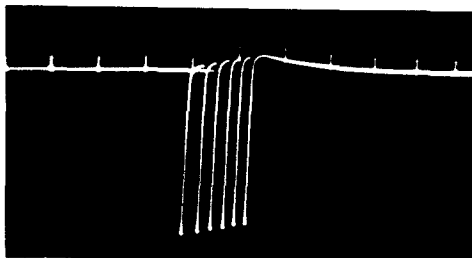


1800

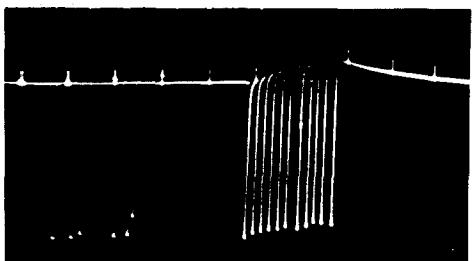
FIG. 11



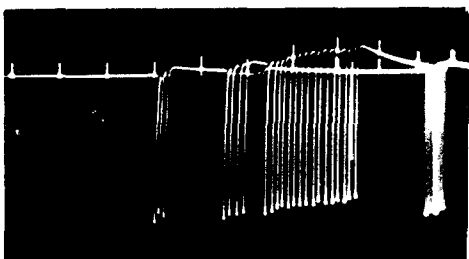
A



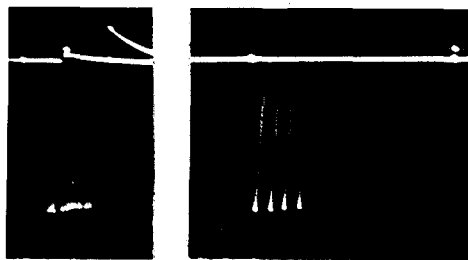
B



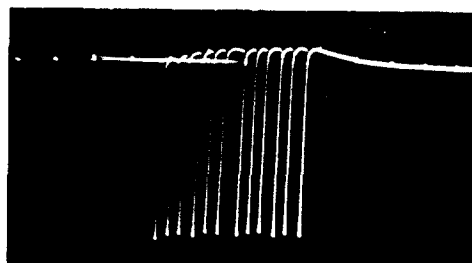
C



D



E



F

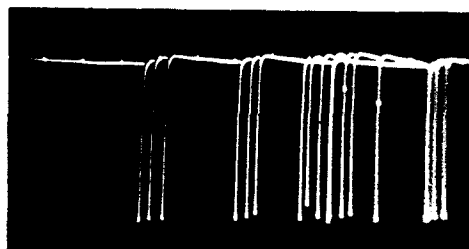


FIG. 12

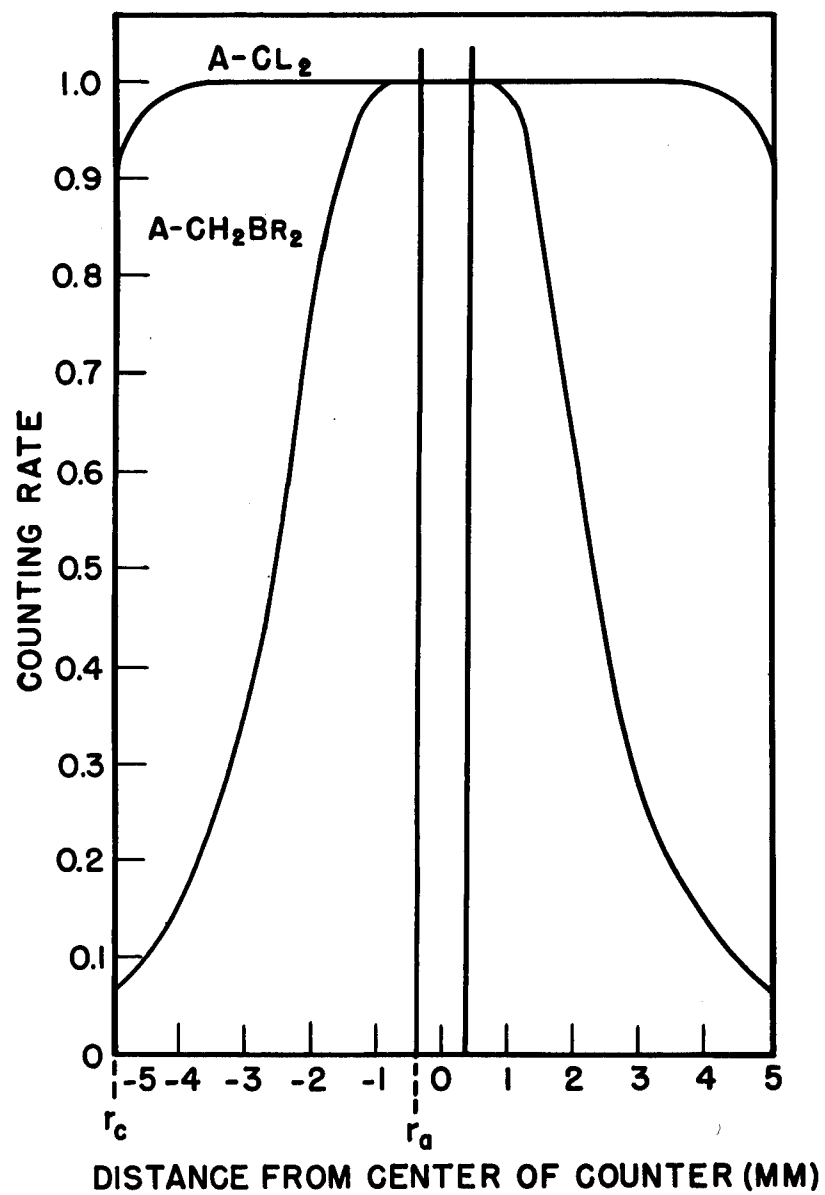


FIG. 13

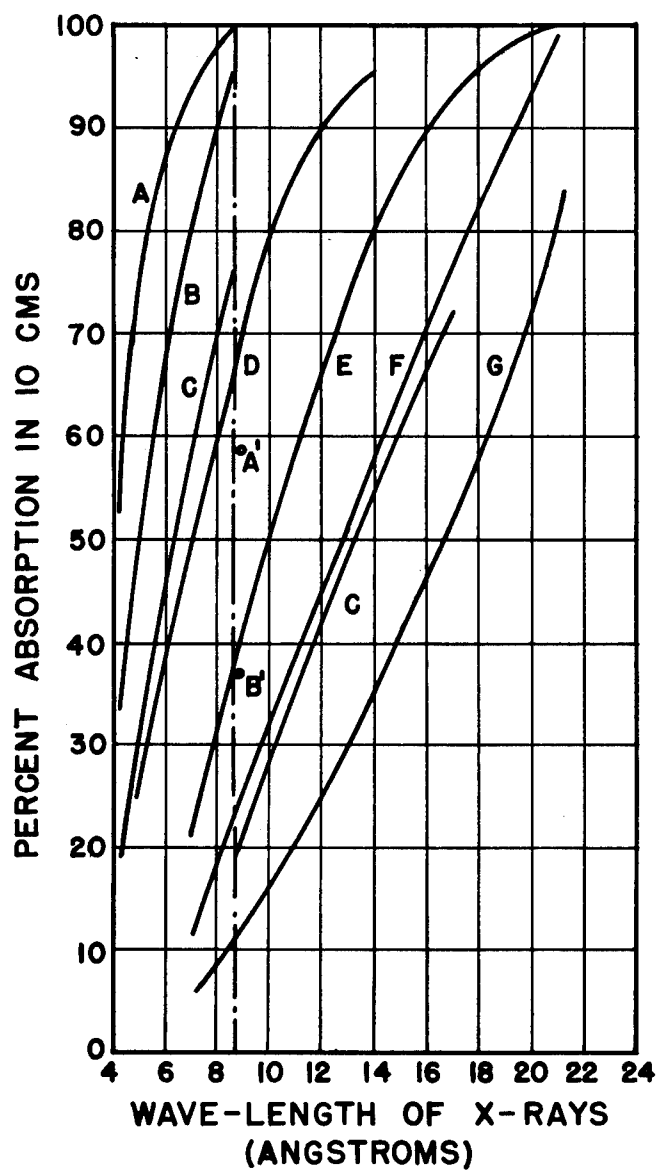
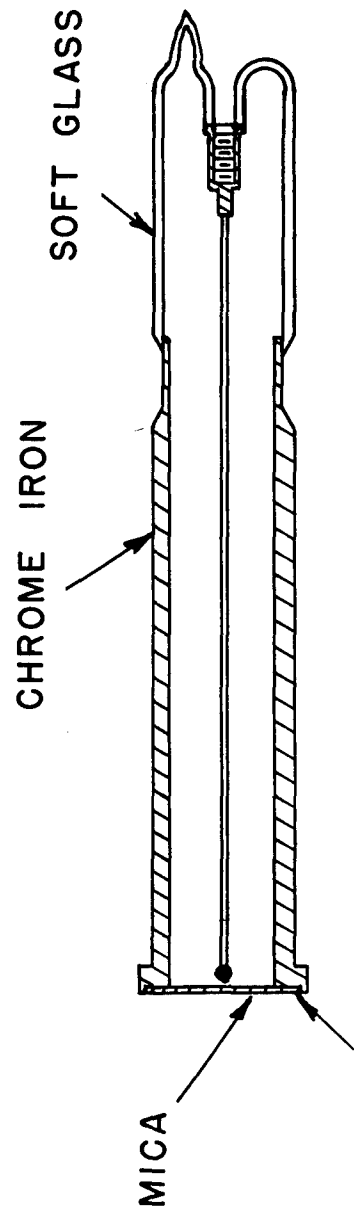
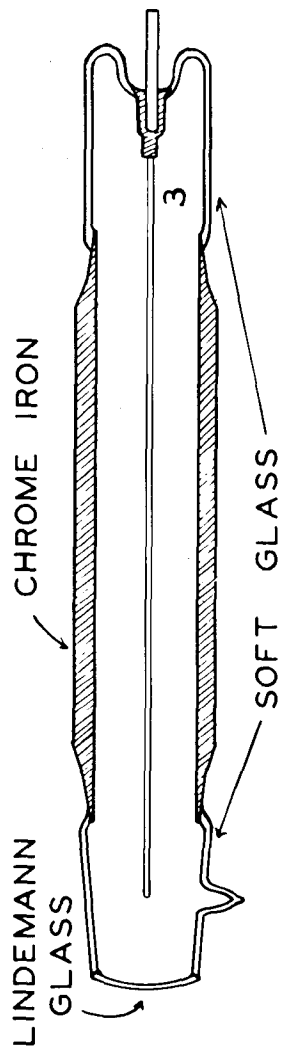
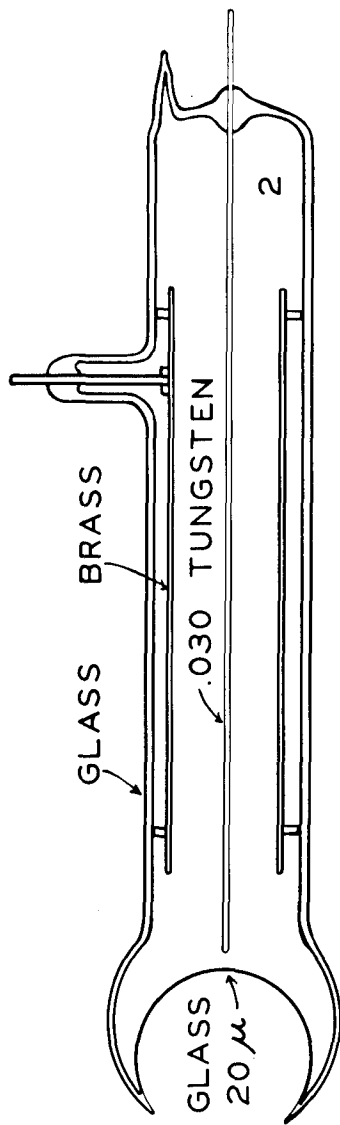


FIG. 14



MICA - GLASS - IRON SEAL

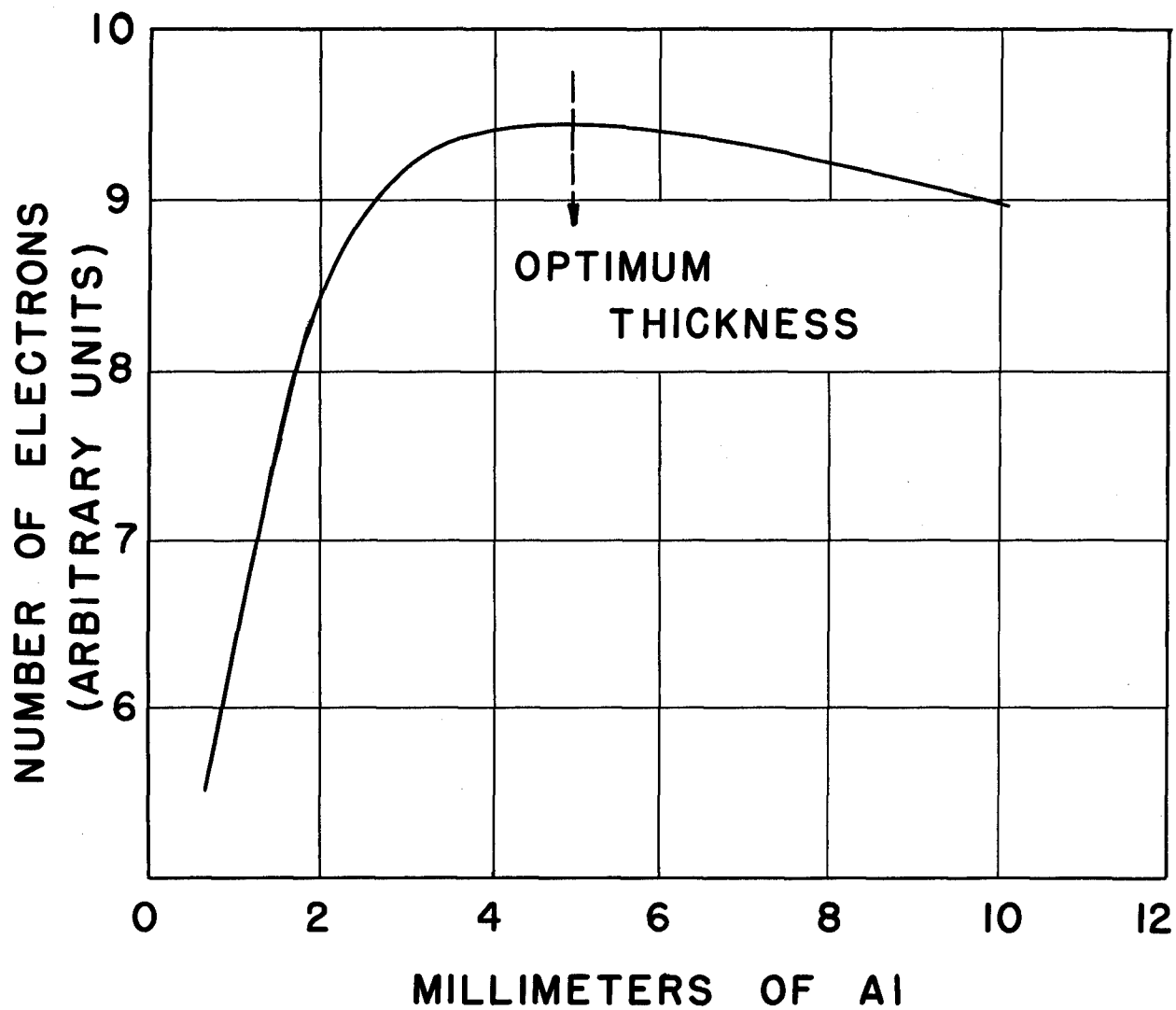


FIG. 16

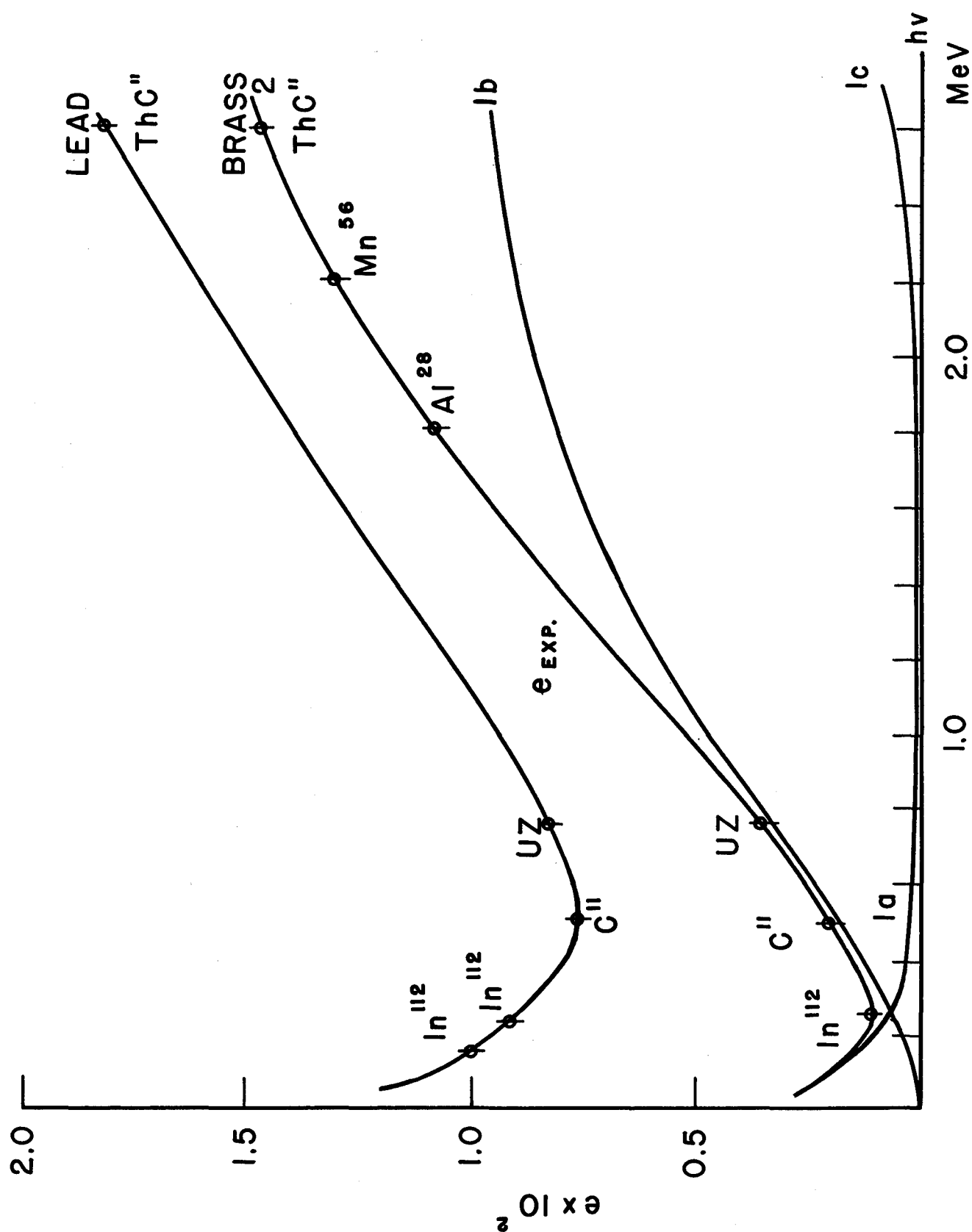


FIG. 17

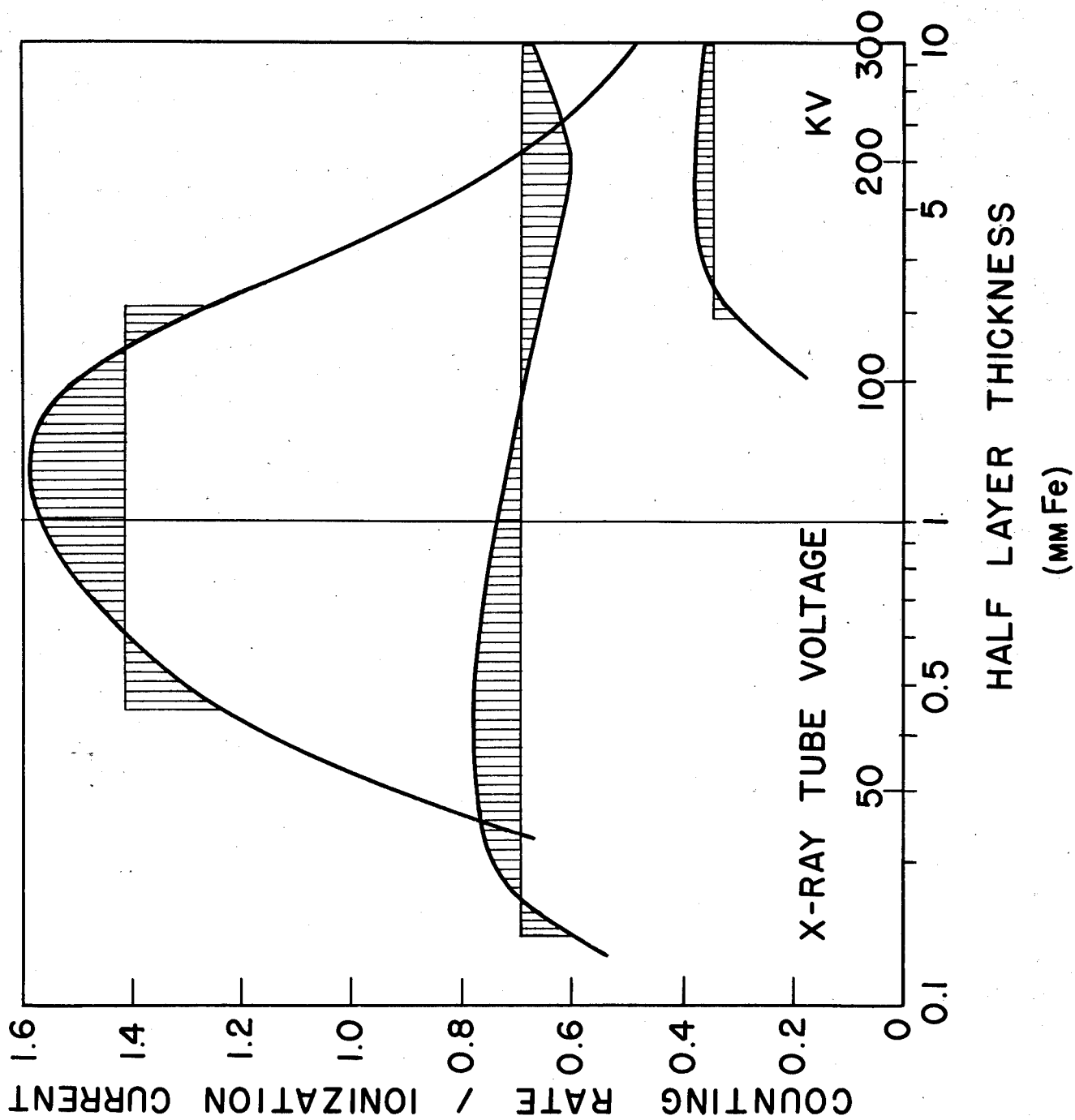


FIG. 18

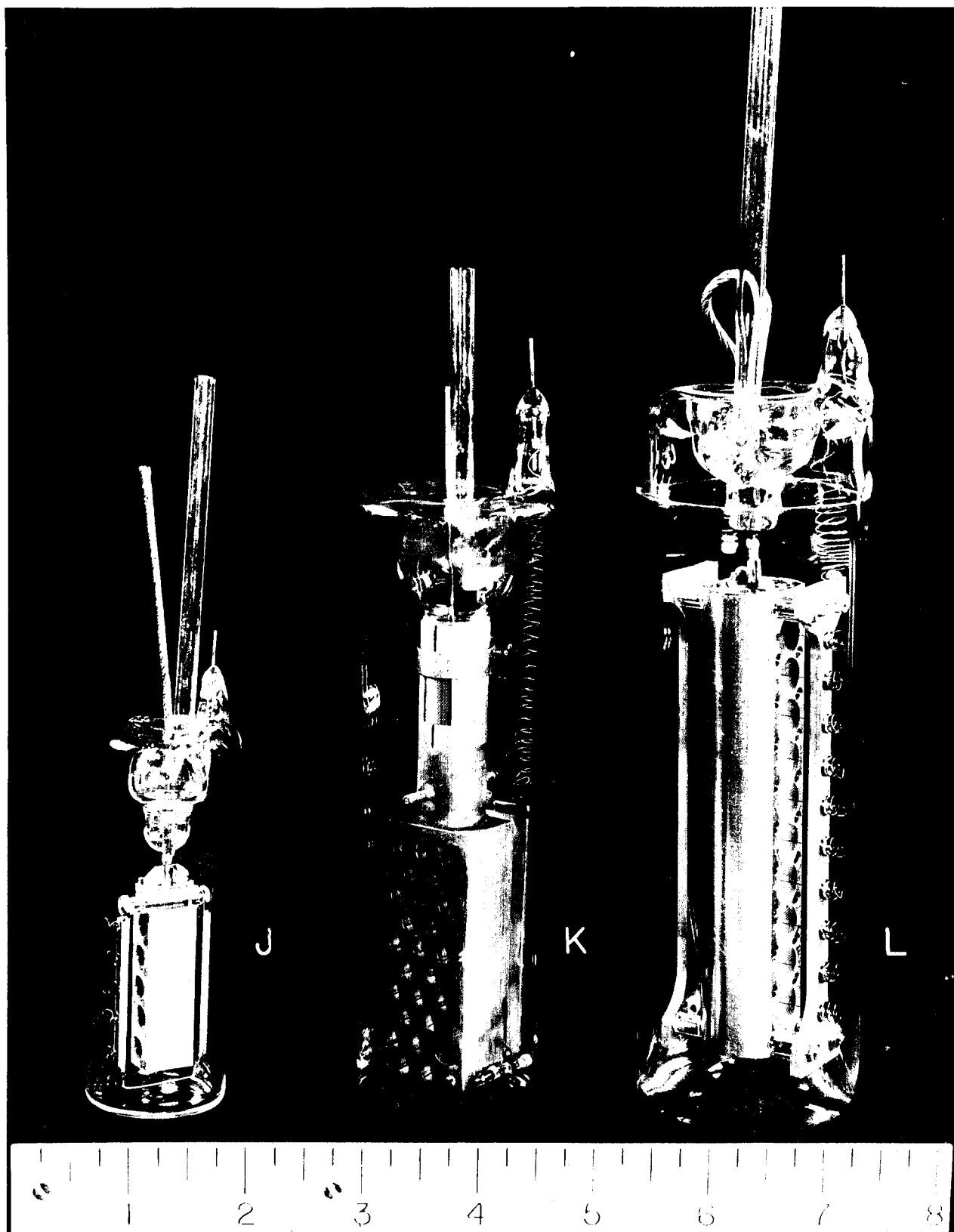


FIG. 19



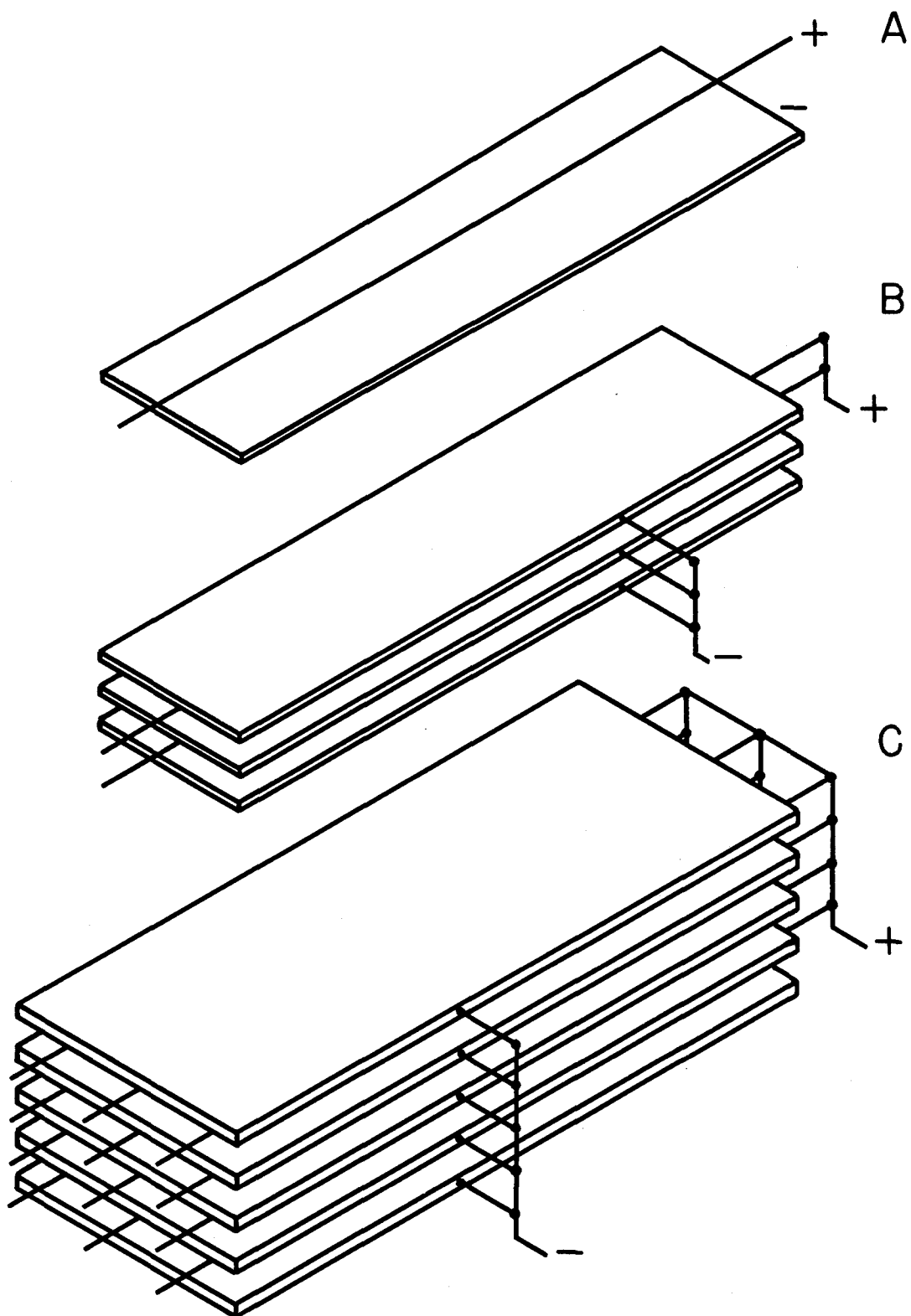


FIG. 20

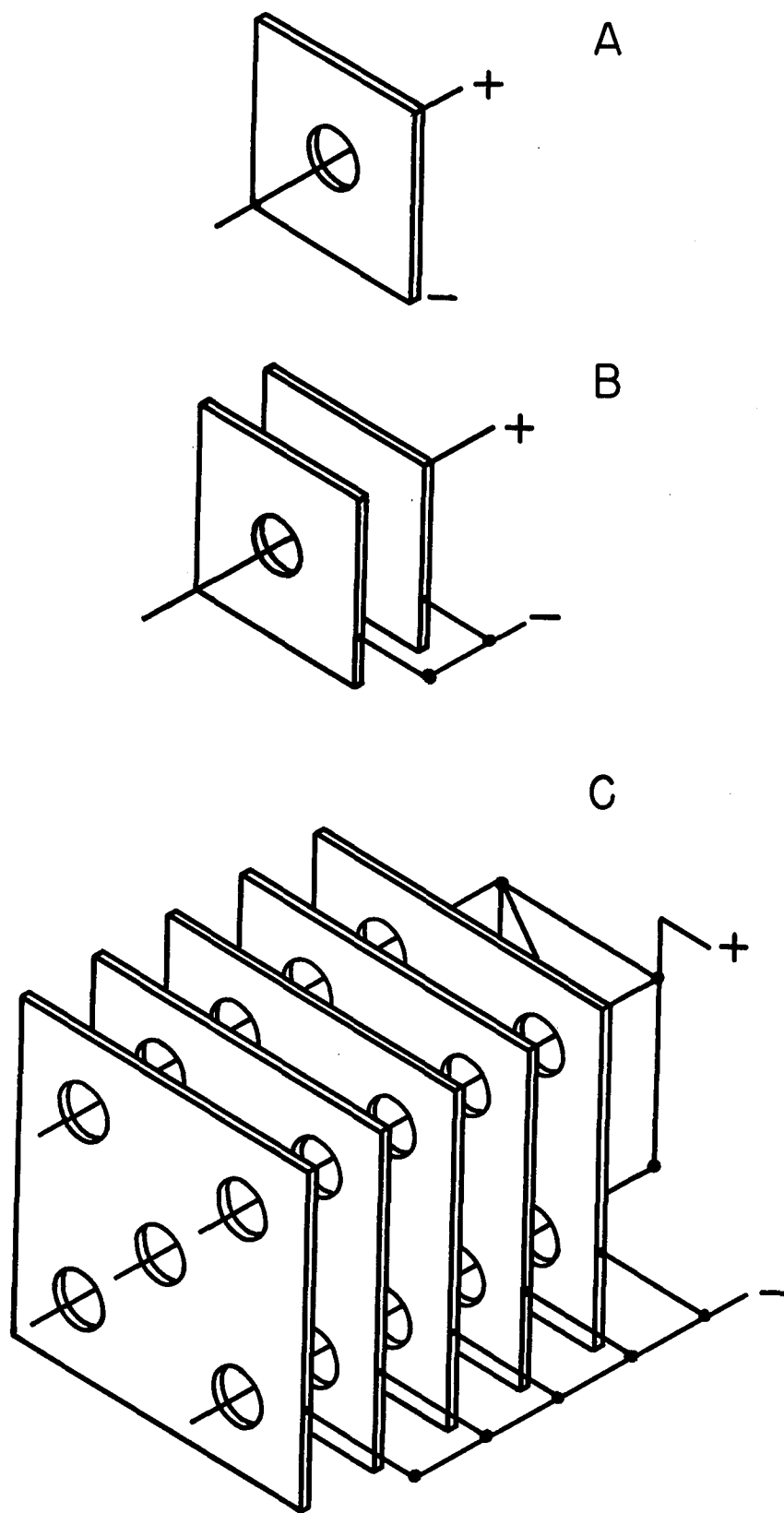


FIG. 21

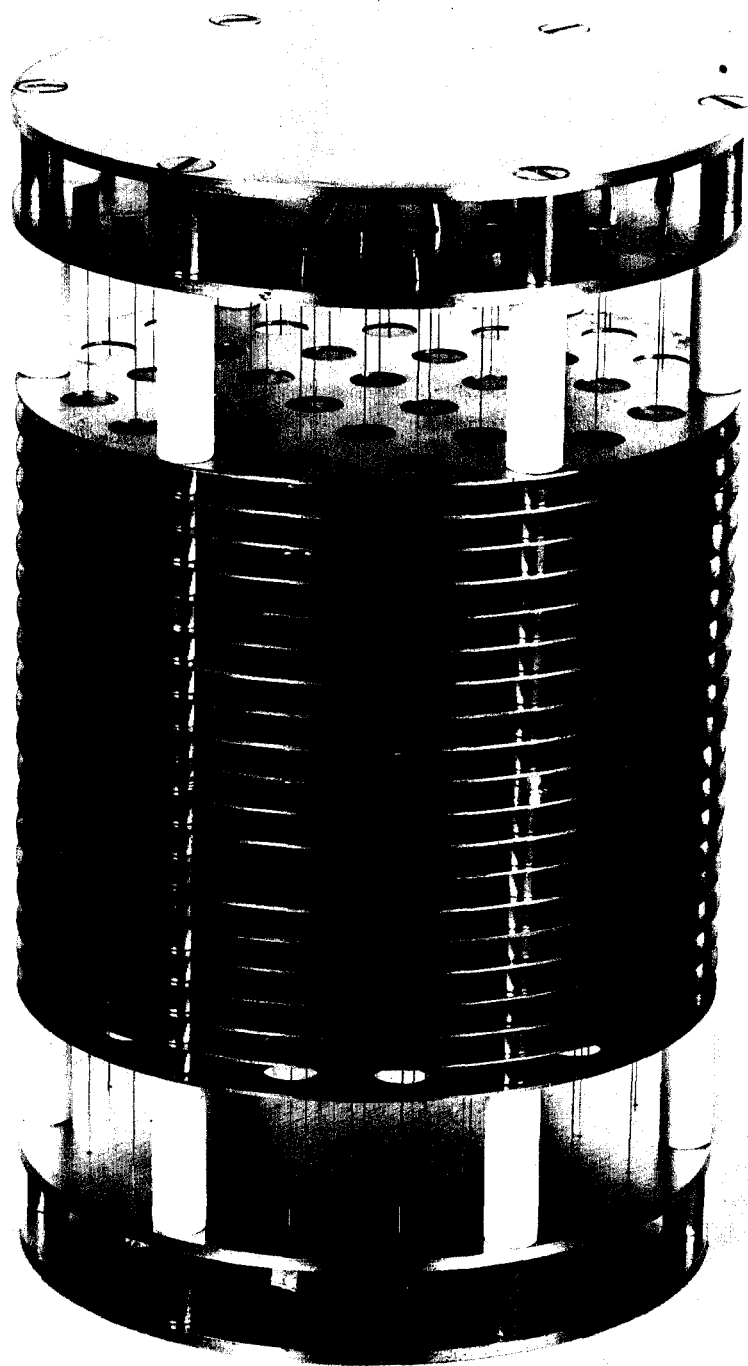


FIG. 22

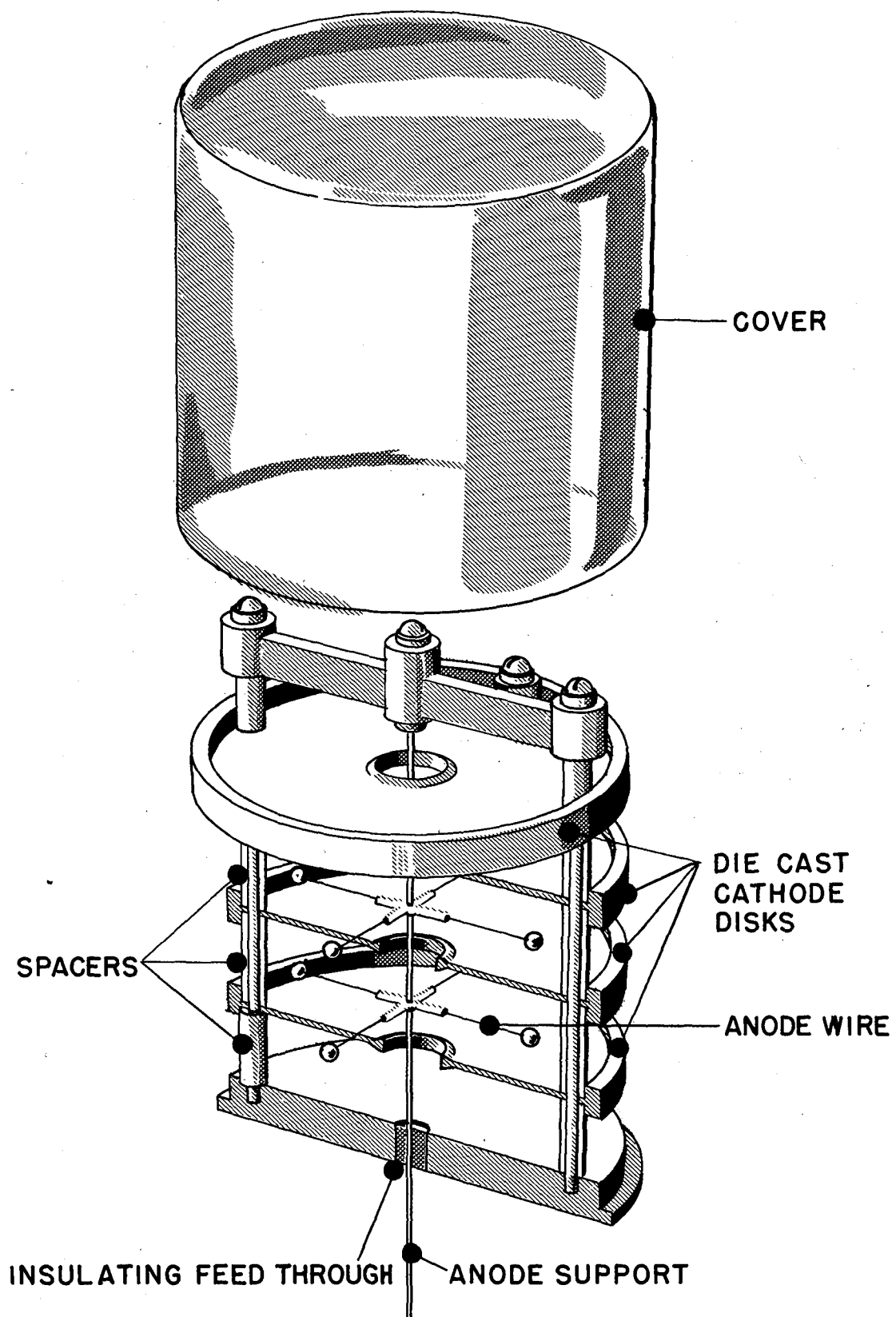
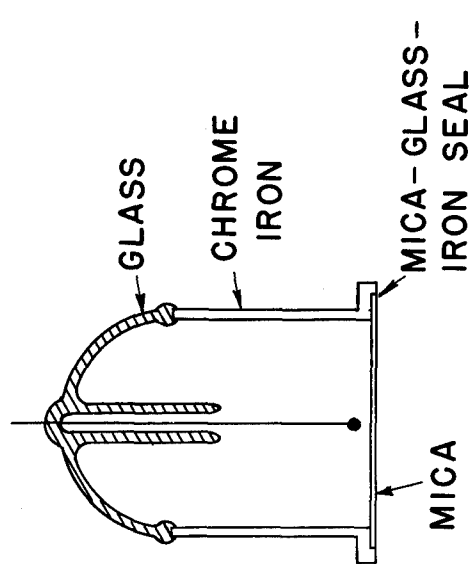
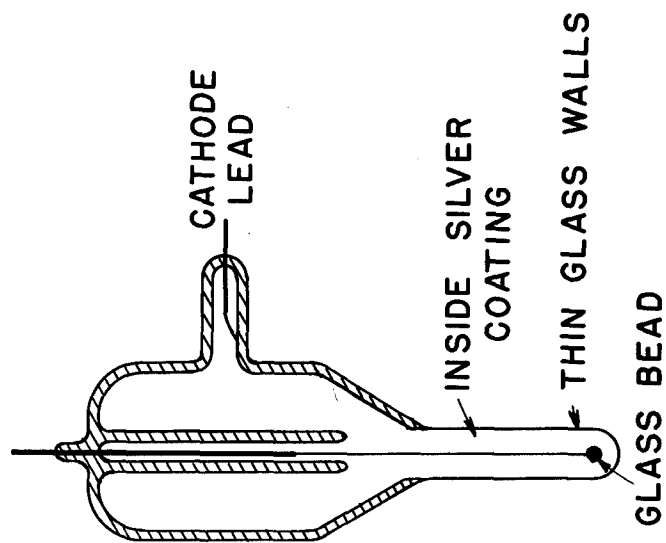


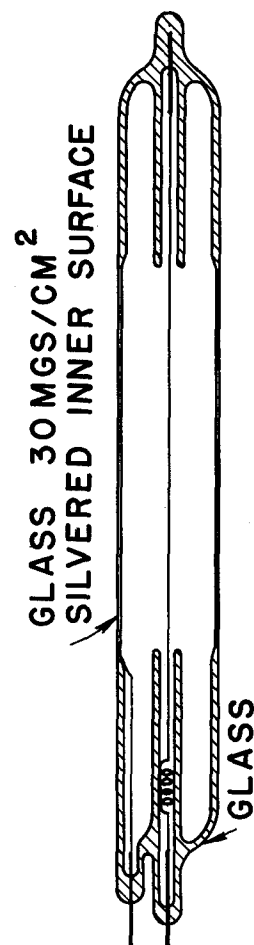
FIG. 23



A. END MICA WINDOW COUNTER



B. THIN WALL DIPPING COUNTER



C. THIN WALL BETA COUNTER

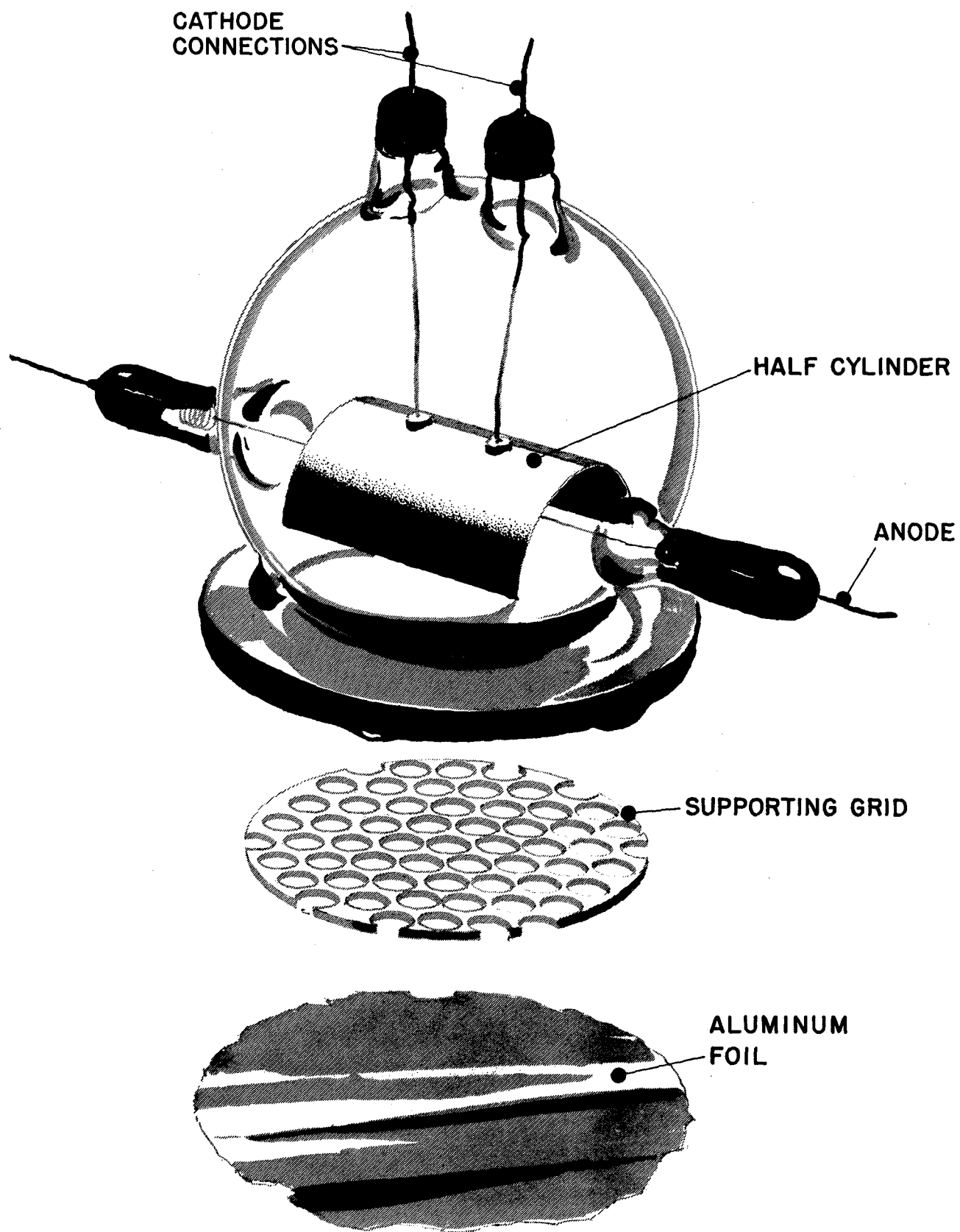


FIG. 25

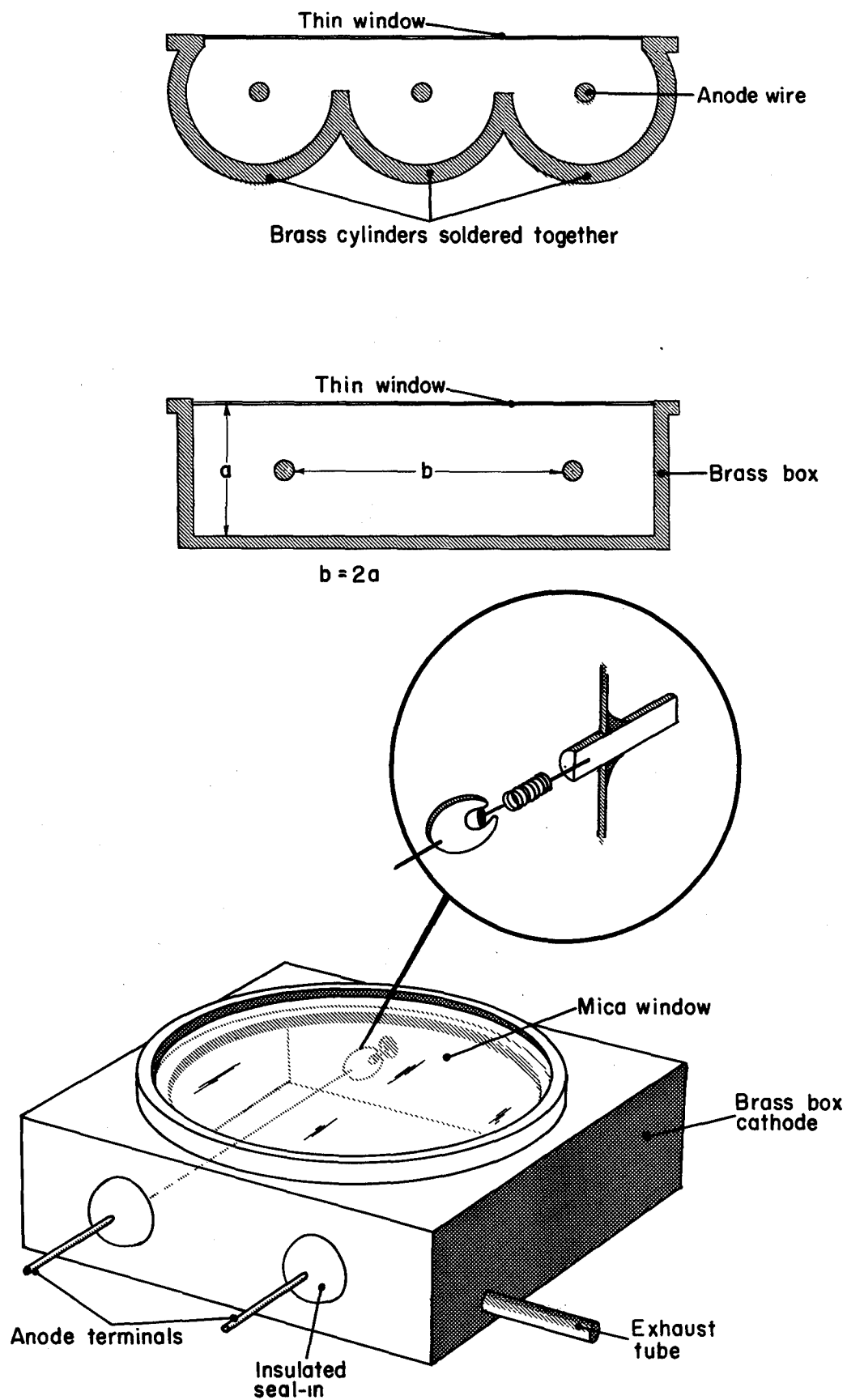


FIG. 26

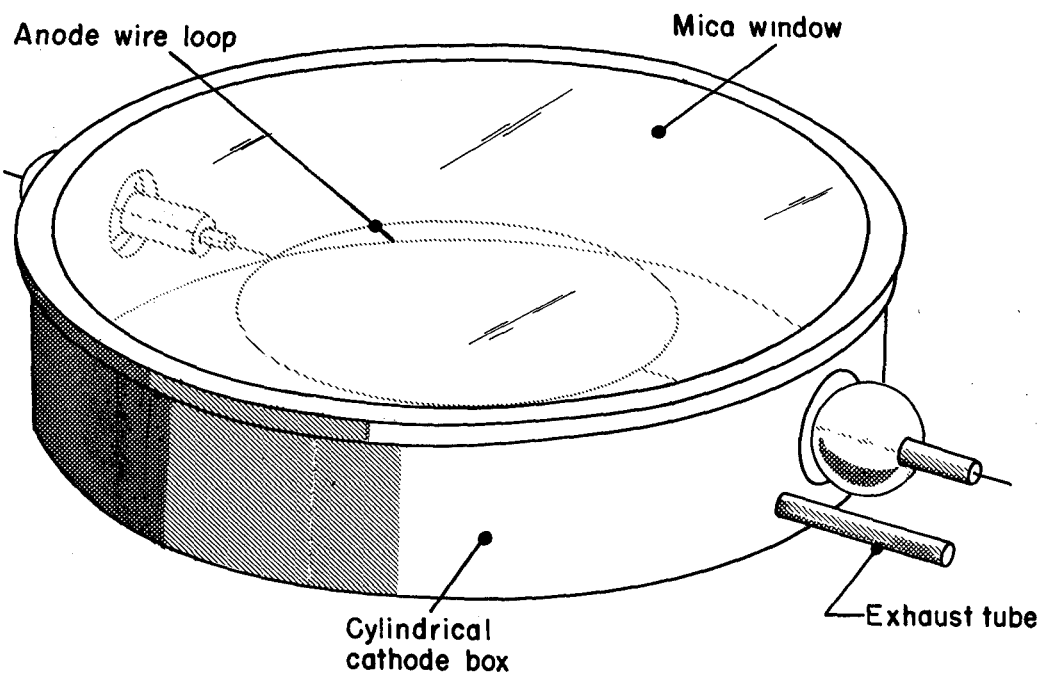
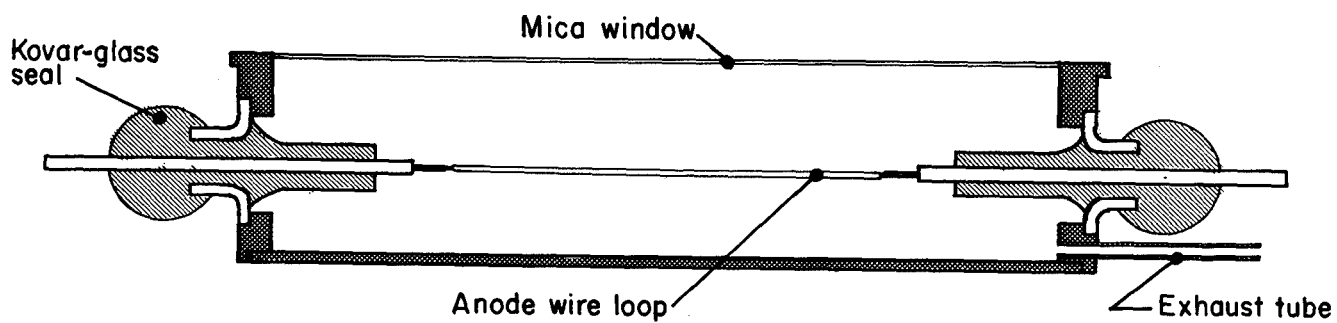
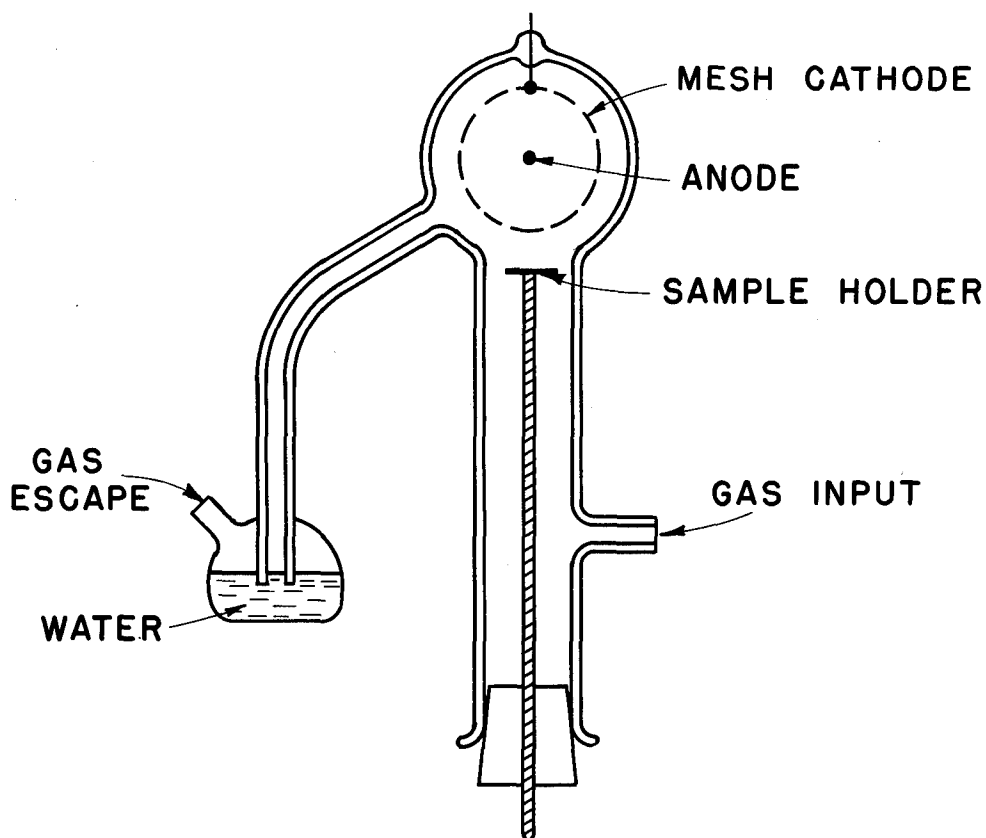
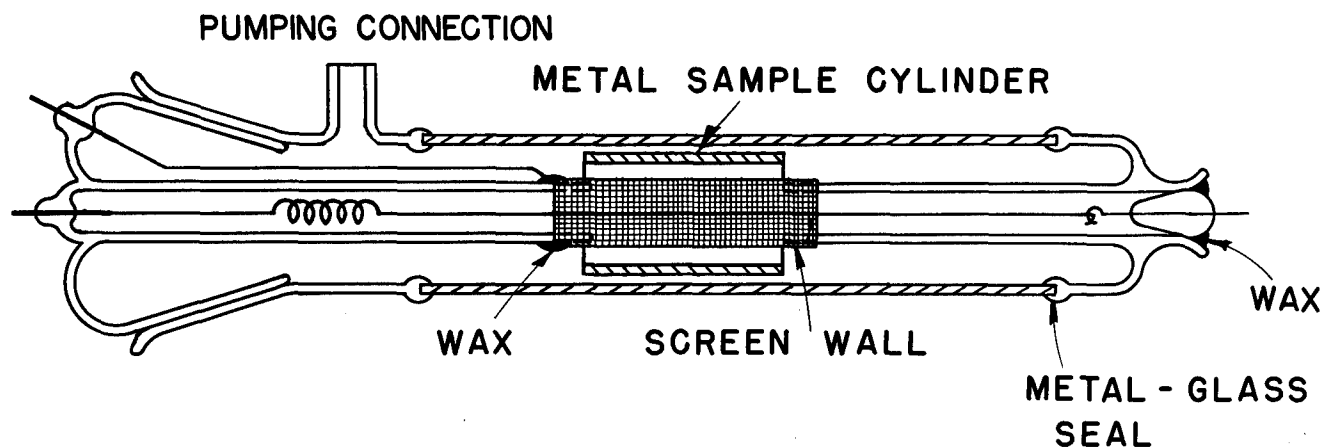


FIG. 27



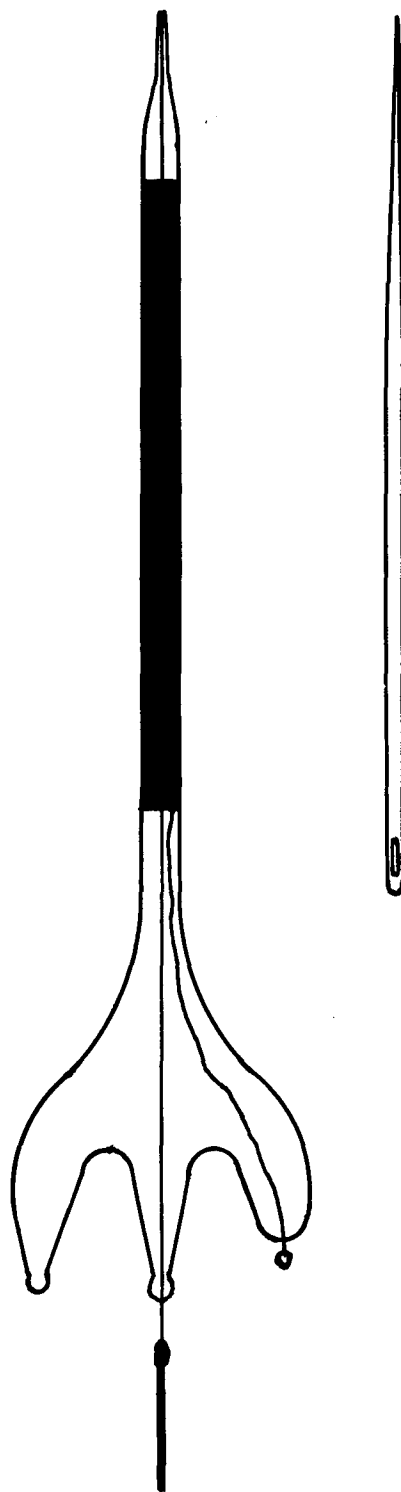
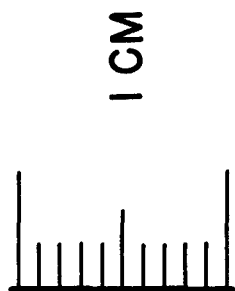


A. GAS-FLOW COUNTER



B. SCREEN WALL COUNTER

DEMOUNTABLE WINDOWLESS BETA COUNTERS



MINIATURE GEIGER - MULLER COUNTER  
THE SEWING NEEDLE IS INCLUDED FOR SIZE  
COMPARISON.

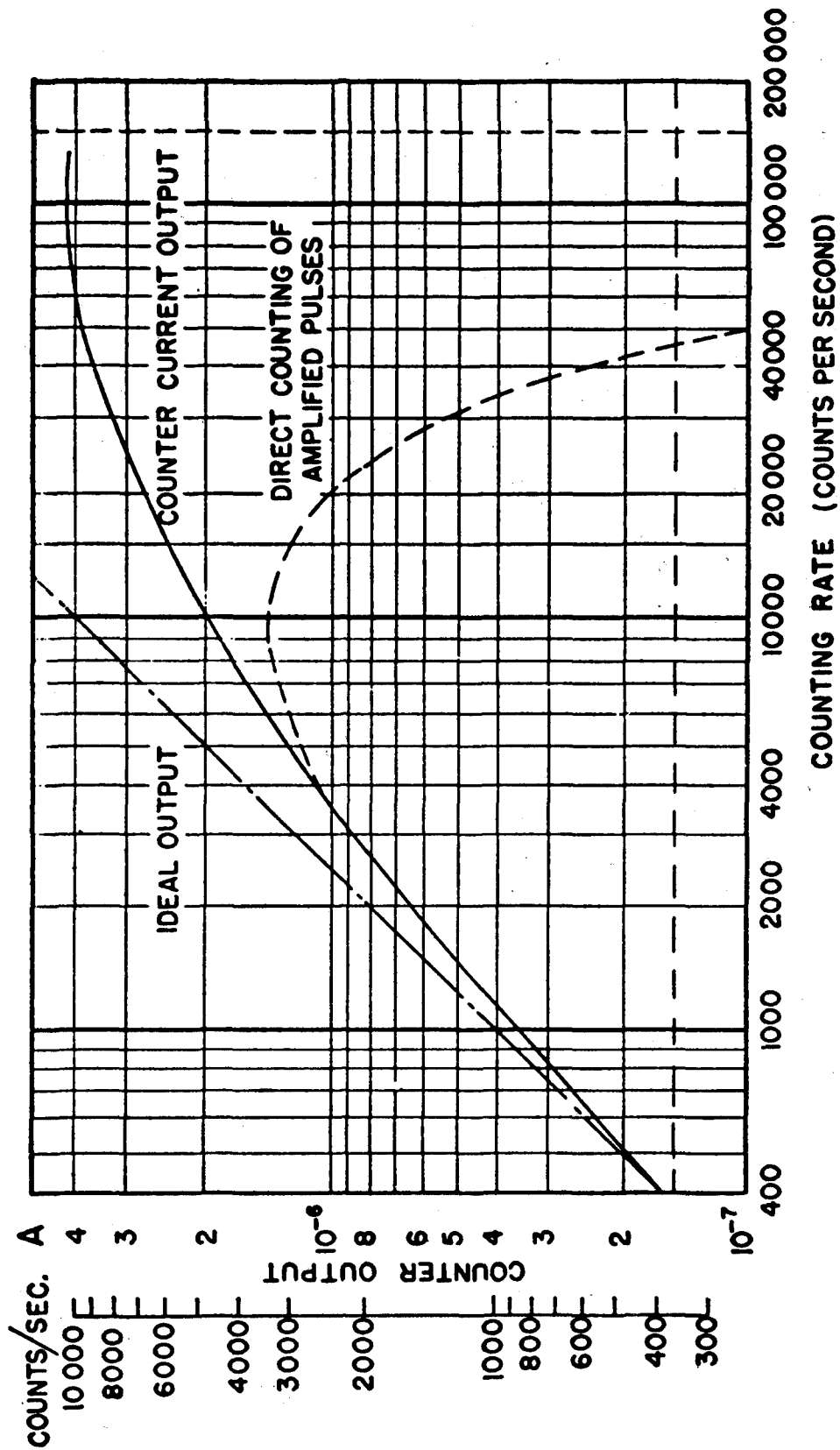


FIG. 30

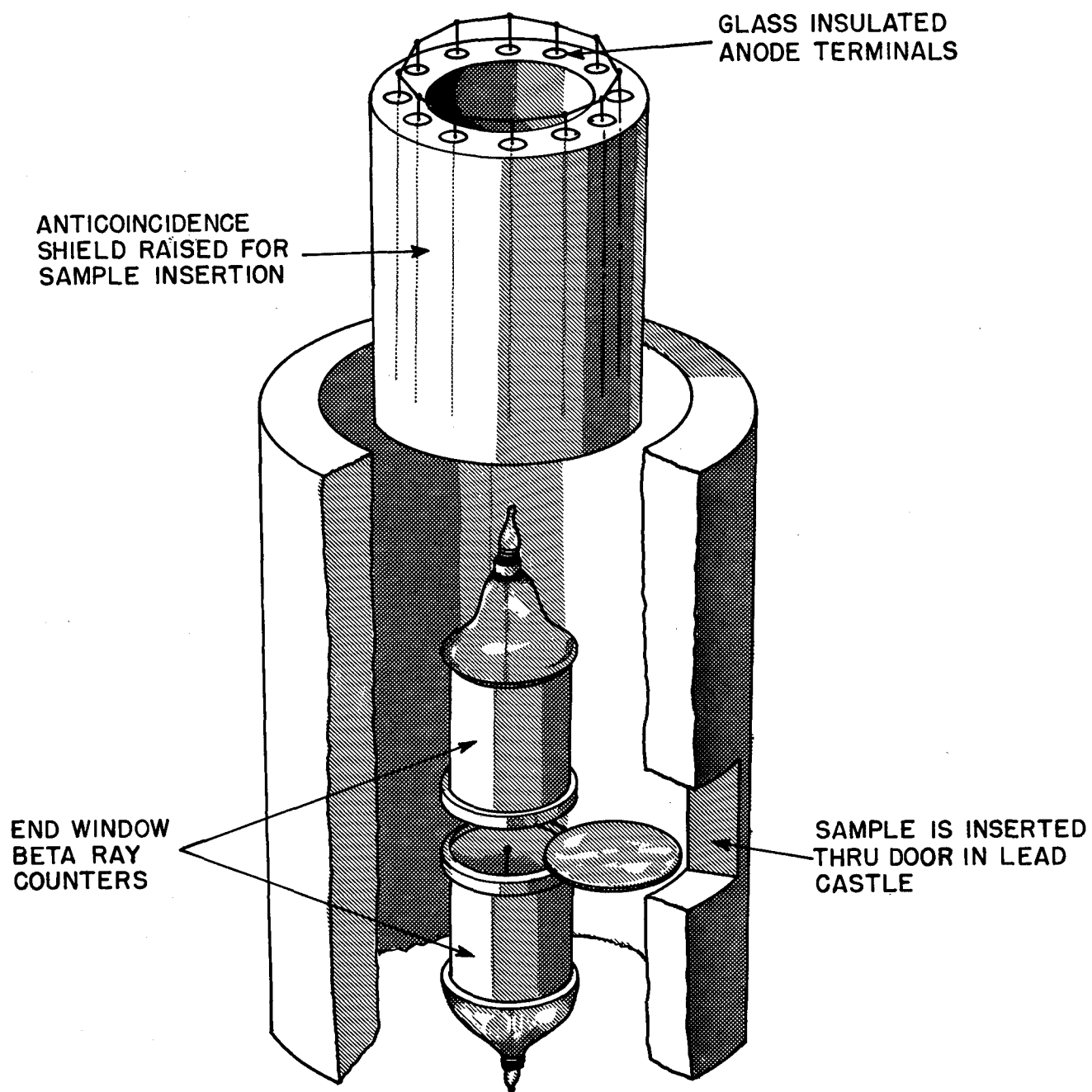


FIG. 31

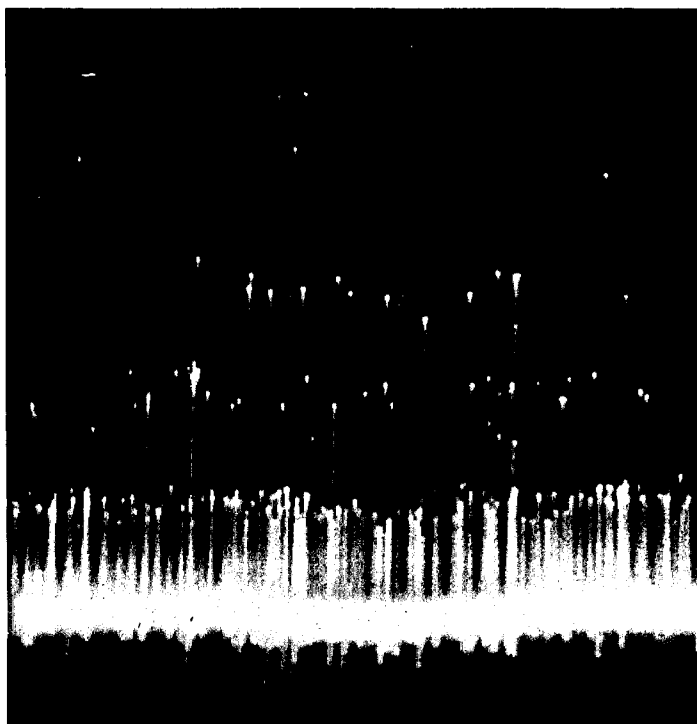


FIG. 32

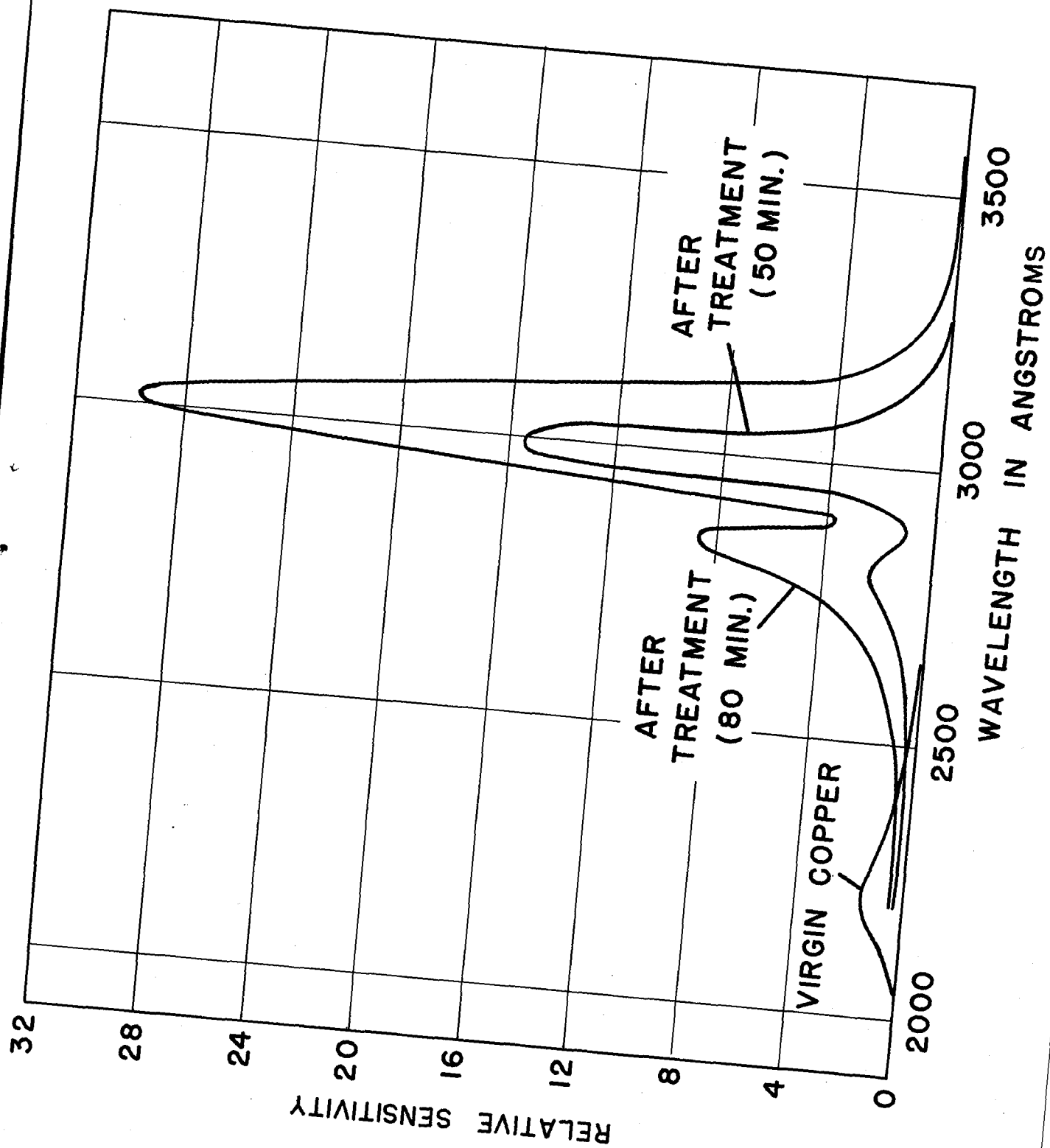


FIG. 33

Doc# 196986

- 1 OF 1
- 1 - AD NUMBER: B196664
- 2 - FIELDS AND GROUPS: 18/4, 7/5, 20/8
- 3 - ENTRY CLASSIFICATION: UNCLASSIFIED
- 5 - CORPORATE AUTHOR: OFFICE OF NAVAL RESEARCH ARLINGTON VA
- 6 - UNCLASSIFIED TITLE: GEIGER COUNTER TUBES.
- 8 - TITLE CLASSIFICATION: UNCLASSIFIED
- 11 - REPORT DATE: 25 MAY 1949
- 12 - PAGINATION: 125P MEDIA COST: \$ 11.00 PRICE CODE: AB
- 18 - MONITOR ACRONYM: XB
- 19 - MONITOR SERIES: ~~ONR~~ NRL
- 20 - REPORT CLASSIFICATION: UNCLASSIFIED
- 22 - LIMITATIONS (ALPHA): DISTRIBUTION: DTIC USERS ONLY.
- 23 - DESCRIPTORS: \*PHOTONS, \*GEIGER COUNTERS, DETECTION,  
-- DEMONSTRATIONS, HIGH VELOCITY, PARTICLES, ENERGETIC PROPERTIES,  
-- TUBES.
- 24 - DESCRIPTOR CLASSIFICATION: UNCLASSIFIED
- 25 - IDENTIFIERS: MULLER
- 26 - IDENTIFIER CLASSIFICATION: UNCLASSIFIED
- 27 - ABSTRACT: SINCE THE FIRST DEMONSTRATION OF THE TUBE COUNTER BY  
-- GEIGER AND MULLER IN JULY 1928, THE UNUSUAL SENSITIVITY OF SUCH  
-- COUNTERS HAS FOUND WIDESPREAD APPLICATIONS IN THE DETECTION OF  
-- HIGH SPEED PARTICLES AND ENERGETIC PHOTONS. THE EXTENSIVE  
--  
-- LITERATURE ON GEIGER COUNTERS IS NOT ONLY INDICATIVE OF THEIR  
-- MAINFOLD USES BUT IS ALSO A MEASURE OF THE DIVERGENCE OF THE  
-- THEORIES DEVISED TO EXPLAIN THEIR MECHANISMS AND THE NUMEROUS  
-- RECIPES PRESCRIBED FOR THE PREPARATION OF GOOD COUNTERS. (JG) P.2
- 28 - ABSTRACT CLASSIFICATION: UNCLASSIFIED
- 29 - INITIAL INVENTORY: 1
- 33 - LIMITATION CODES: 12
- 35 - SOURCE CODE: 265250
- 36 - ITEM LOCATION: DTIC
- 40 - GEOPOLITICAL CODE: 5110
- 41 - TYPE CODE: N
- 43 - IAC DOCUMENT TYPE:

Please change Field 5 To Read "NAVAL Research Laboratory"  
Field 10 Friedman, H. 251 950

APPROVED FOR PUBLIC  
RELEASE - DISTRIBUTION  
UNLIMITED

Completed  
1-19-2000